



**EVALUATING THE MODEL OF MULTI – GLOBAL
NAVIGATION SATELLITE SYSTEMS (GNSS)
CONSTELLATION TO MITIGATE THE MULTIPATH SIGNALS.**

By

Bhekinkosi Pheneas Madonsela

Submitted in the fulfilment of the requirements of the degree of Doctor of
Engineering in Electrical Power Engineering in the Faculty of Engineering and
the Built Environment at the Durban University of Technology

March 2023

Submitted by:

10 May 2023

.....
Student: Bhekinkosi Madonsela (21208384)

.....
Date

Approved for Final Submission by:

14 May 2023

.....
Supervisor: Prof I.E Davidson

.....
Date

Approved for Final Submission by:

15 May 2023

.....
Co-supervisor: Dr E Mukubwa

.....
Date

Approved for Final Submission by:

18 May 2023

.....
Co-supervisor: Dr K Moloi

.....
Date

ABSTRACTS

The Global Navigation Satellite Systems (GNSS) are evolving continuously and are being used in many applications across the world. The GNSS is used in electrical industries, the banking sector, the agricultural sector, the transportation and logistics sectors, etc. The architecture and operation of the GNSS is made up of three subdivisions: the space section, control section, and user section. The space segment consists of the satellite constellation to generate and emit the GNSS code phase and carrier phase signals. The space segment further stores and broadcasts the navigation data that is uploaded to the system by the GNSS controllers. For accurate Position, Velocity and Time (PVT), the satellite constellation must have at least three or four satellites visible to the GNSS receiver. The control segment is also known as the ground segment and is accountable for the complete operations of the GNSS. The ground segment further controls and preserves the conformation files of the satellite constellation, updates the navigation data to all satellites, controls the atomic clock of the GNS, and predicts the satellite ephemeris. The user segment is made up of GNSS receivers; their purpose is to receive the GNSS signal that contains the code phase and carrier phase to determine the pseudorange and other observables. There are numerous issues that obstruct the application of the GNSS across all sectors mentioned above; those are signal attenuation in the satellite channels, signal diffraction, and signal multipath. Hence, this thesis focused on mitigating the GNSS multipath signal by investigating the concept of Combined Signal Detection (CSD). The purpose was to reduce the impact of signal degradation and further enable the GNSS receivers to withstand the signal degradation in deep rural areas. There are numerous existing methodologies to mitigate multipath signal and improve the positioning, velocity and timing in urban areas. However, the proposed CSD approach provided the better performance by using the vector detection of all visible satellites to improve (DP) Direct Positioning, High Sensitivity (HS) and clock bias.

Furthermore, the capabilities of the Global Positioning Systems (GPS) and Galileo satellites are integrated to accommodate the adoption of CSD concept. The CSD concept require the GNSS receiver that is capable of processing multi-frequencies. The multi-constellation GNSS receiver use numerous satellites that are in space, such as Global Positioning Systems (GPS) satellites, BeiDou satellites, Galileo satellites, and Glonass satellites. However, the similarities between the constellations is investigated before the system is integrated for multi-constellation. The concept of CSD proved to be capable of mitigating the signal multipath without introducing an external device or circuit. This thesis further provided the comprehensive analysis of sources that contribute towards the signal degradation.

DECLARATION

I hereby declare that this dissertation is my original work, every cited or text have been properly referenced and has not been previously submitted in part or totality for another degree in this or any other University.

Submitted by:

.....

Bhekinkosi P Madonsela

.....

Date

Student Number: 21208384

Approved for Final Submission by:

.....

Supervisor: Prof I.E Davidson

.....

Date

Approved for Final Submission by:

.....

Co-supervisor: Dr E Mukubwa

.....

Date

Approved for Final Submission by:

.....

Co-supervisor: Dr K Moloi

.....

Date

DEDICATION

This research work is devoted to my God.

To my son and siblings

ACKNOWLEDGEMENTS

Primarily, I give praise to my Lord for His vast kindness, care, love and protection.

My thoughtful appreciation goes to Prof. I.E. Davidson for his commitments, vital remarks, and valuable recommendations for this research work.

I acknowledge him for his time, endless guidance, financial supports, reassurances, and valuable inputs thorough supervision in order to realize the objectives of this work. I further acknowledge the thesis review and administration work made by Dr K Moloi

Furthermore, I will like to extend my appreciation to the Durban University of Technology for the financial assistance via Space Science this support helped me to carry out my studies thoroughly and complete my program.

I extremely appreciate my parents and siblings for their honorable supports, prayers, sympathetic and encouragements.

Finally, I wish to thank all my friends and well-wishers in the Electrical Engineering Department, Faculty of the Engineering and the Built Environment, the entire University, and beyond for their intuitive advice and inspirations

TABLE OF CONTENTS

Page number

ABSTRACT	I
DECLARATION	III
DEDICATION	IV
ACKNOWLEDGEMENTS	V
TABLE OF CONTENTS	VI
LIST OF FIGURES	XII
LIST OF TABLES	XV
LIST OF ABBREVIATIONS	XVI
CHPATER ONE: Introduction	
1.1. The General introduction	1
1.2. The GNSS Overview.....	3
1.3. The GNSS Measurements and Data Modelling.....	4
1.4. Motivation and Problem formulation	7
1.5. The Thesis Objectives	9
1.6. The Thesis Overview and Arrangement.....	10
1.7. Publications and Research outputs.....	10
1.8. The Contribution of the study.....	11
CHAPTER TWO: Literature Review	
2.1. Background.....	12
2.2. The Satellite Communication methodology.....	13
2.3. The GNSS Architecture	15
2.4. The GNSS Frequency Distribution	19
2.5. The GNSS Spectrum and Signal Structure	21
2.6. The GNSS Satellite Constellation.....	23
2.7. The GPS Spreading code and Signal Structure	25
2.7.1. The C/A spectrum code	27
2.7.2.The P spectrum code	27
2.7.3. The Y spectrum code	28
2.7.4.The L1C code	28
2.7.5.The L2CM code.....	28

2.7.6.The L2 CL code	28
2.7.7.The M code	28
2.7.8.The L5 code	28
2.7.8. The non-standardized code	29
2.8. The Glonass Satellite Constellation	29
2.9. The Galileo Spreading Code and Signal Structure	30
2.9.1. The Galileo E1	31
2.9.2. The Galileo and GPS L-5	31
2.9.3. The Galileo E6.....	32
2.10. The BeiDou Satellite Constellation	32
2.11. The Generation and Broadcasting of the Satellite Signal.....	34
2.12. Navigation Centre Frequency and Spectral Density.....	36
2.13. The Signal Processing and Receiver Design.....	37
2.13.1. The Digital Processing of the GNSS signal in the Receiver.....	41
2.13.2. The Correlation Process.....	42
2.14. Summary and Conclusion.....	43
CHAPTER THREE: The GNSS Multipath Propagation and Mitigating Techniques	
3.1. Background.....	44
3.2. Modelling of the Propagation and Transmission Channel.....	46
3.2.1. The Transmitter and Receiver Antenna.....	47
3.2.2. Multipath Propagation Channel.....	47
3.3. The GNSS transfer function along the transmission channel	48
3.3.1. Received signal	48
3.3.2. Exact model	49
3.3.3. Wideband model	49
3.3.4. Narrowband model.....	50
3.4. Multipath parameters definition and computation	50
3.4.1. Acquisition block	54
3.4.2. Tracking blocks	55
3.5. The Influence of the multipath signal on the GNSS code and Pseudorange	57

3.5.1. The definition of the raw code and range error for multipath signals	57
3.5.2. Evaluating the estimate of the code delay in the presence of multipath signal	59
3.6. The Analysis of the GNSS Multipath Performance for Both Galileo and GPS	61
3.7. The GNSS Signal Modulation and Processing	62
3.7.1. Weighted Multipath Error Envelopes	64
3.7.2. The Predictable Multipath Errors Code	66
3.8. The GNSS Signal Multipath Detection and Monitoring	68
3.8.1. SNR Monitoring.....	68
3.8.2. The C/N_0 profiles recordings.....	68
3.8.3. The Link Based Budget Computations.....	69
3.8.4. Monitor Thresholds.....	69
3.8.5. Code minus Carrier (CMC) Monitoring.....	70
3.8.6. MEDLL.....	72
3.9. The techniques to mitigate the multipath signals.....	72
3.9.1. The Narrow Correlation.....	73
3.9.2. Special Antennas.....	74
3.9.3. The double delta correlator	75
3.9.4. Carrier Smoothing.....	75
3.10. Summary and Conclusion.....	80

CHAPTER FOUR: The Combined Signal Detection of the Diverse GNSS signals to mitigate the carrier multipath in linear combination

4.1. Background.....	81
4.2. The working Principle of Collective detection of the GNSS multipath signals.....	82
4.3. Methodology of CSD application in GNSS signals: Combining GPS and Galileo – multiconstellation.....	85
4.4. Methodology and data collection.....	86
4.4.1. Architecture of the proposed hybrid scheme.....	86

4.4.2. The Complexity analysis.....	88
4.4.3. GNSS signal Acquisition of the CSD technique.....	89
4.4.4. Satellite Data Collection.....	91
4.4.4. GNSS glAB simulation scenario and analysis.....	93
4.4.6. Challenges in weak GNSS signal acquisition.....	95
4.5. Simulation Results and analysis.....	101
4. 6. GNSS data bit transmission and transition for CSD technique	115
4.6.1. Main Signal Differences.....	115
4.6.2. The relative distribution of power	115
4.6.3. The rate of bit data transmission and transition.....	116
4.6.4. Elevation angle.....	118
4.7. Summary and Conclusion.....	119
CHAPTER FIVE : Investigating the signal Acquisition	
Degradation Sources in GNSS receivers	
5.1. Background.....	121
5.2. Sources of GNSS signal degradation.....	121
5.2.1 Ionosphere Influences.....	122
5.2.1.1. Location-dependent variations.....	123
5.2.1.2. Variations due to solar activity.....	123
5.2.1.3. Diurnal variations.....	123
5.2.1.4. Seasonal variations.....	123
5.2.1.5. Ionosphere refraction.....	124
5.2.2. Overview of Tropospheric Propagation.....	124
5.2.2.1. Tropospheric Influences.....	124
5.2.2.2. Tropospheric scintillation.....	124
5.2.2.3. Tropospheric path delay.....	125
5.2.2.4. Tropospheric attenuation.....	125
5.2.2.5. Doppler Shift.....	125
5.2.2.6. User Environment.....	125
5.2.2.7. Shadowing Effects.....	125
5.2.2.8. Interference and Jamming.....	126
5.3. Effect of GNSS code Doppler.....	126
5.3.1 Generalities on code Doppler Effect.....	128

5.3.2. Rate of change of the Doppler frequency.....	132
5.4. The Numerical modelling of the signal degradation sources and distorted correlation function.....	134
5.4.1. The infinite GNSS bandwidth and limited bandwidth.....	138
5.4.2. The advanced GNSS signal carrier and code phase Tracking.....	139
5.4.3. Detection of the new multipath signal.....	144
5.5. Summary and conclusion.....	146
CHAPTER SIX: Investigating the performance of the CSD and the multi-signal GNSS receiver	
6.1. Background.....	147
6.2. The analysis of the GNSS multi frequency and Constellation.....	148
6.2.1. Multi-GNSS acquisition.....	151
6.2.2. Multi-GNSS tracking.....	152
6.2.3. Multi-correlator tracking.....	152
6.3. The acquisition to tracking transition of the GNSS Signal.....	153
6.4. Modelling and results discussion.....	153
6.5. GNSS satellite availability.....	168
6.7. Summary and Conclusion.....	170
CHAPTER SEVEN : Conclusion and recommendations	
7.1 Background.....	172
7.2. Chapters synopses	172
7.3. The recommendations for future work	175
References	176

LIST OF FIGURES

Page number

CHAPTER ONE

Figure 1.1: The causes of the signal degradation during the propagation.....	1
Figure 1.2: The pseudo-range measurements content.....	2
Figure 1.3: The indoor GNSS application and their power losses.....	3

CHAPTER TWO

Figure 2.1: The satellite structures.....	13
The concept of satellite communication.....	14
Figure 2.3: The architecture of GNSS systems.....	15
Figure 2.4: The control segment of the GPS.....	16
Figure 2.5: The Glonass control segment.....	17
Figure 2.6: The Galileo ground segment.....	18
Figure 2.7: The GNSS frequency bands.....	19
Figure 2.8: The Legacy and modified GPS frequency bands.....	26
Figure 2.9: The Glonass frequency bands.....	29
Figure 2.10: The Galileo frequency bands.....	31
Figure 2.11: The BeiDou frequency bands.....	33
Figure 2.12: The Intonation and Broadcast of the GPS signal through L1 Frequency link.....	35
Figure 2.13: The Intonation and Broadcast of the GPS signal through L5 Frequency link.....	35
Figure 2.14: The illustration of the GPS L1 Centre frequency.....	36
Figure 2.15: The illustration of the GPS L5 Centre frequency.....	37
Figure 2.16. The basic architecture of Hybrid Galileo/GPS Receiver Concept.....	38

CHAPTER THREE

Figure 3.1: The Representation of the GNSS multipath.....	45
Figure 3.2: The combine propagation and transmitting channel.....	47
Figure 3.3: Advanced architecture of GNSS receiver.....	53
Figure 3.4: The Standardized correlator outputs for GPSL5 – without signal multipath.....	60

Figure 3.5: The standardized correlator outputs for GPSL5 – with the single echo signal.....	61
Figure 3.6: The analysis of the autocorrelation function between the three sample signals.....	63
Figure 3.7: The Evaluation of weighted multipath error envelopes between the three GNSS sample signals.....	65
Figure 3.8: The filtration of the simulated CMC observation.....	71
Figure 3.9: The 8th Butterworth filter for CMC observables.....	71
Figure 3.16: The Evaluation of the Code discriminator and multipath error envelope for the chip rated 0.1 for the Narrow Correlator.....	73
Figure 3.11: The flow chart of the proposed MLE of the amplitude, code delay.....	79
CHAPTER FOUR	
Figure 4.1: Forecast of the GNSS clock bias domain in CSD.....	84
Figure 4.2: The block illustration of the CSD and data processing.....	86
Figure 4.3: The flowchart of the CSD processing steps.....	87
Figure 4.3: The illustration of the Galileo and GPS satellite visibility (skyplot).....	91
Figure 4.4: Data collection (free and minimum signal obstruction).....	92
Figure 4.5: Data collection (minimum and maximum signal obstruction).....	92
Figure 4.6: The main menu page of the gLAB software for modelling.....	93
Figure 4.7: Satellite constellation selection and process configuration.....	94
Figure 4.8: The view of the carrier phase ambiguities, skyplot of visible satellite and measuring the noise or multipath signal.....	94
Figure 4.9: The configuration of the GNSS inputs for processing.....	95
Figure 4.10: The GNSS signal acquisition grid for PRN5.....	96
Figure 4.11: The GNSS signal acquisition for PRN5.....	97
Figure 4.12: Cross correlation between Galileo E1 and GPS L-1C.....	103
Figure 4.13 : Power Spectral Density (PSD) of signals in the L1 band.....	104
Figure 4.14 : Cross-correlation functions of CBOC signals.....	106

Figure 4.15: The changes of the correlator spacing for pilot and data channels: For Galileo E1 for CBOC modulation where the chip code effect is zero.....	107
Figure 4.16 : The Data and Pilot cross-correlation.....	108
Figure 4.17 : GNSS signals spreading codes correlation.....	108
Figure 4.18: The function of GNSS auto-correlation for Galileo E1B bandwidths.....	109
Figure 4.19: The function of GNSS auto-correlation for the GPS L1 C/A bandwidths and RF end.....	110
Figure 4.20: Code and satellite tracking for three bandwidths.....	111
Figure 4.21: The GNSS signal acquisition block.....	112
Figure 4.22: Probability of detection when acquiring both component.....	112
Figure 4.23: The Likelihood of detection for GPS L5 or Galileo E5a if the coherent integration period is equal to 1ms.....	114
Figure 4.24: The effect of post – coherent integration on the SNR for GPS L5 and Galileo E5.....	114
Figure 4.25 : The GPS C/A range measurements for Channel 1, PRN17 and Stream1	116
Figure 4.26 : The PDI Epoch of the phase discriminator GPS C/A.....	117
Figure 4.27: The code discriminator for GPS C/A.....	118
Figure 4.28 : The illustration of the code, phase and SNR against elevation angle.....	119

CHAPTER FIVE

Figure 5.1: The changes of the GNSS spreading code.....	127
Figure 5. 2: The Signal acquisition for GPS L-5, GPS L-1C and Galileo.....	130
Figure 5.3 : The illustration of the carrier phase at IF (a), the code phase at IF (B) and the correlation function at IF (c).....	136
Figure 5.4: The Doppler, Code phase and C/N0 for correlation envelope..	137
Figure 5.5: Changes of the Doppler, Code phase and C/N0 for correlation Envelope.....	137
Figure 5.6: The illustration of the thermal code noise for code error Tracking.....	138

Figure 5.7: The loop gain calculation and modelling of the GNSS receiver.....	140
Figure 5.8: The code filter for GPS C/A: Range, velocity and Acceleration.....	141
Figure 5.9: Figure 5.8: The carrier filter for GPS C/A: Range, velocity and Acceleration.....	142
Figure 5.10: The correlation phase of the signal in the 2nd quadrant for GPS.....	142
Figure 5.11: The illustration of the phase lock indicator for GPS C/A.....	143
Figure 5.12: The performance evaluation for GLRT+ CSD and CSD only techniques.....	146
CHAPTERS SIX	
Figure 6.1: The acquisition block of the innovative GNSS receivers.....	151
Figure 6.2: The post-processing of the GNSS signal and real-time operation.....	154
Figure 6.3 Probabilities of detection as a function of the total.....	155
Figure 6.4: The C/N_0 for numerous satellites GPS L1 frequency band measured on the receiver.....	157
Figure 6.5: The correlation for visible and invisible satellites to the Receiver.....	157
Figure 6.6: The data bit transition for 1st and 2nd transitions during correlation function.....	158
Figure 6.7: The GNSS clock offset: Lowest and highest clock offset.....	159
Figure 6.8: The illustration of the coherent integration against probability of detection.....	160
Figure 6.9: The changes of the C/N_0 due to the changes in detection likelihood.....	160
Figure 6.10: GPS only and Galileo+GPS+ BeiDou satellite visibility.....	161
Figure 6.11: The visibility of satellite constellation (skyplot).....	161
Figure 6.12: The number of visible satellites.....	161
Figure 6.13: The illustration of the horizontal error for multi- constellation.....	162
Figure 6.14: The Galileo E1 autocorrelation for code Doppler	

that is equal to 10 ms.....	162
Figure 6.15 : The GPS L-1 C/A autocorrelation for code Doppler that is equal to 10ms.....	163
Figure 6.16 : The signal amplitude variation during Autocorrelation.....	164
Figure 6.17 : The GNSS signal Losses during autocorrelation because of the code Doppler changes.....	165
Figure 6.18: The illustration of the PDI integrated correlator magnitudes for GPS C/A code.....	166
Figure 6.19: The illustration of the non-coherent power variations for GPS C/A.....	167
Figure 6.20 : The illustration of the C/N_0 GPS C/A code over the specific period.....	167
Figure 6.21 : The GPS satellites availability in the area with no obstruction.....	168
Figure 6.22: The GPS satellites visibility in the area with signal obstruction.....	169
Figure 6.23: The GPS and Galileo satellites visibility in a location with maximum signal obstruction.....	169

LIST OF TABLES

Page number

CHAPTER TWO

Table 2-1: The summary GNSS1 constellation.....23

Table 2-2: The summary GNSS2 constellation.....24

Table 2-3: The Beidou Phase III navigation signals.....34

CHAPTER THREE

Table 3-1: The parameters for GPS and Galileo constellation.....67

CHAPTER FOUR

Table 4-1: The spreading codes of the GPS and Galileo
Constellations.....100

Table 4-2: The frequency domain, data access, frequency band,
bandwidth and centre frequencies for Galileo and GPS.....102

CHAPTER FIVE

Table 5-1 : The duration of the spreading code and the
offset of the incoming Doppler frequency.....129

Table 5-2: The parameters of the GPS L-1 C/A and power levels.....130

Table 5-3: The received power levels for Galileo and
GPS constellations.....131

Table 5-4: The sources of the frequency offset.....133

Table 5-5 : The code and carrier Doppler for GPS and Galileo
Satellites.....131

Table 5-6: The offset values for GPS and Galileo over single chip.....136

CHAPTER SIX

Table 6-1: The characteristics of GPS L-1 C/A and
Galileo E1 correlation function for CBOC modulation scheme.....160

LIST OF ABBREVIATIONS

A-GPS	Assisted GPS
ADC	Analogue Digital Conversion
AGC	Automatic Gain Control
ANSS	Augmentation Navigation Satellite Systems
ASIC	Application Specific Integrated Circuit
A-TOA	Adapted Time Of Arrival
BER	Bit-Error-Rate
BJ	Bump and Jump
BOC	Binary Offset Carrier
C/A	Coarse Acquisition
CBOC	Composite BOC
CCRW	Code Composite Ranging Waveform
CD	Combined Detection
CDMA	Code Division Multiple Access
CGR	Cognitive GNSS Radio
CGR-DB	CGR Data Base
CNR	Carrier-to-Noise Ratio
CP	Cooperative Positioning
CS	Commercial Services
CSD	Combined Signal Detection
CPS	Cognitive Positioning System
DGPS	Differential Global Positioning System
DLL	Delay-Locked Loop
DNS	Decca Navigation System
DPLL	Differential Phase-Locked Loop
DSP	Digital Signal Processor
DSSS	Direct Sequence Spread Spectrum
EDSM	Enhanced Dynamic Spectrum Management
EGNOS	European Geostationary Navigation Overlay Service
EITHSCD	Efficient and Innovative Technique of High Sensitivity Combined Detection
EKF	Extended Kalman Filter

FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Array
FM	Frequency Modulation
FT	Fourier Transform
GAGAN	GPS Aided GEO Augmented Navigation
GLRT	Generalized Likelihood Ratio Test
GNC	Guidance Navigation and Control
GPS	Global Positioning System
GNSS	Global Navigation Satellite System
GSS	Galileo Sensor Stations
GTRF	Galileo Terrestrial Reference Frame
HEDSM	Hybrid Enhanced Dynamic Spectrum Management
HS-CD	High Sensitivity Collective Detection
HS-CGR	High Sensitivity Cognitive GNSS Receiver
HS-GNSS	High Sensitivity GNSS
HS-GPS	High Sensitivity GPS
IDFT	Inverse Discrete Fourier Transform
IF	Intermediate Frequency
IGS	International GNSS Service
IGSO	Inclined Geo Synchronous Orbit
INS	Inertial Navigation System
IR	Infra-Red
ISP	Intelligent Signal Processing
JNR	Jammer-to-Noise Ratio
LBS	Location-Based Services
LHCP	Left Hand Circularly Polarized
LNA	Low Noise Amplifier
LORAN	LOng-RAge Navigation
LOS	Line of Sight
LORAN	Long Range Navigation
LS	Laser Station
MBOC	Multiplexed BOC

MCS	Master Control Station
MEDLL	Multipath-Estimating Delay Locked Loop
MSAS	MTSAT Satellite Augmentation System
MTLL	Mean Time to lose Lock
MTTA	Mean Time to Acquire
MUSIC	Multiple Signal Classification
NCO	Numerical Control Oscillator
NNSS	Navy Navigation Satellite System
OBC	On-Board Computer
PC	Personal Computer
PDA	Personal Data Assistant
PFA	Probability of False Alarm
PLL	Phase-Locked Loop
PND	Personal Navigation Devise
PRN	Pseudorandom Noise
RF	Radio Frequency
RFID	Radio Frequency Identification
RHCP	Right Hand Circularly Polarized
RISC	Reduced Instruction Set Computer
RNSS	Regional Navigation Satellite Systems
SBAS	Satellite-Based Augmentation System
SCAN	Signal, Communication, Antenna and Navigation
SCP	Spectral Compression Positioning
SDN	Software Defined Navigation
SDR	Software Defined Radio
SNR	Signal-To-Noise Ratio
SPS	Standard Positioning Services
SV	Space Vehicle
TT&C	Telemetry, Tracking, and Control

CHAPTER ONE

Universal introduction

Chapter one briefly discusses the introduction of this research work and further provide the background, objectives and the structure of the thesis.

1.1. GNSS background

The concept of GNSS is the concept of determining velocity and time for stationary and dynamic applications using relevant integrated technologies and systems. In recent applications, the operation of the GNSS (GLONASS and GPS) is based on radio navigation-based schemes that utilize radio frequency (RF) signals [1]. There are appropriate sets of navigation data signals and codes that are modulated into the wave carrier. Hence, the receiver can calculate the definite distance to estimate how far is the satellite to the end user [2]. The time differential between reception and transmission is very crucial, and needs to be estimated accordingly by the relevant satellite and user on view.

However, the huge setback is that the signal being received on Earth is very weak due to the long distances between the transmitting satellites and receiving antennas. Once the signal is weak, it becomes more vulnerable to signal jamming and interference [3]. Hence this vulnerability leads to signal degradation that increases the noise level in the signal, and in some cases, the receiver finds it very difficult to detect that signal, depending on the whole architecture of the system. Signal interferences and jamming are not the only causes of the weak signal; there are numerous factors that contribute to the signal weakening and degradation [4]. There are three popular categories of signal degradation in the context of GNSS applications, which are understood to be:

- The GNSS architecture failure: This category of signal degradation includes all causes of destructions triggered by nearby satellites or, in some cases, the system architecture [5]. In this case, the evil waveform is generated and emitted from the satellite to the user, as illustrated in Figure 1.1. Hence, this cause of signal degradation is deemed to be intrinsic to the system and architecture of operation.
- The satellite path failure: These types represent the atmospheric sources as the signal travels through the diverse atmospheric layers before reaching the receiver's antenna [6]. This also includes the Doppler shift caused by the relative movements between the satellite and the user.

- The receiver is positioned in a challenging environment; this is more of the signal veiling caused by the buildings, trees, weather, and multipath [7]. Most of the suggested solutions relating to signal destruction or diversion are user-based solutions.

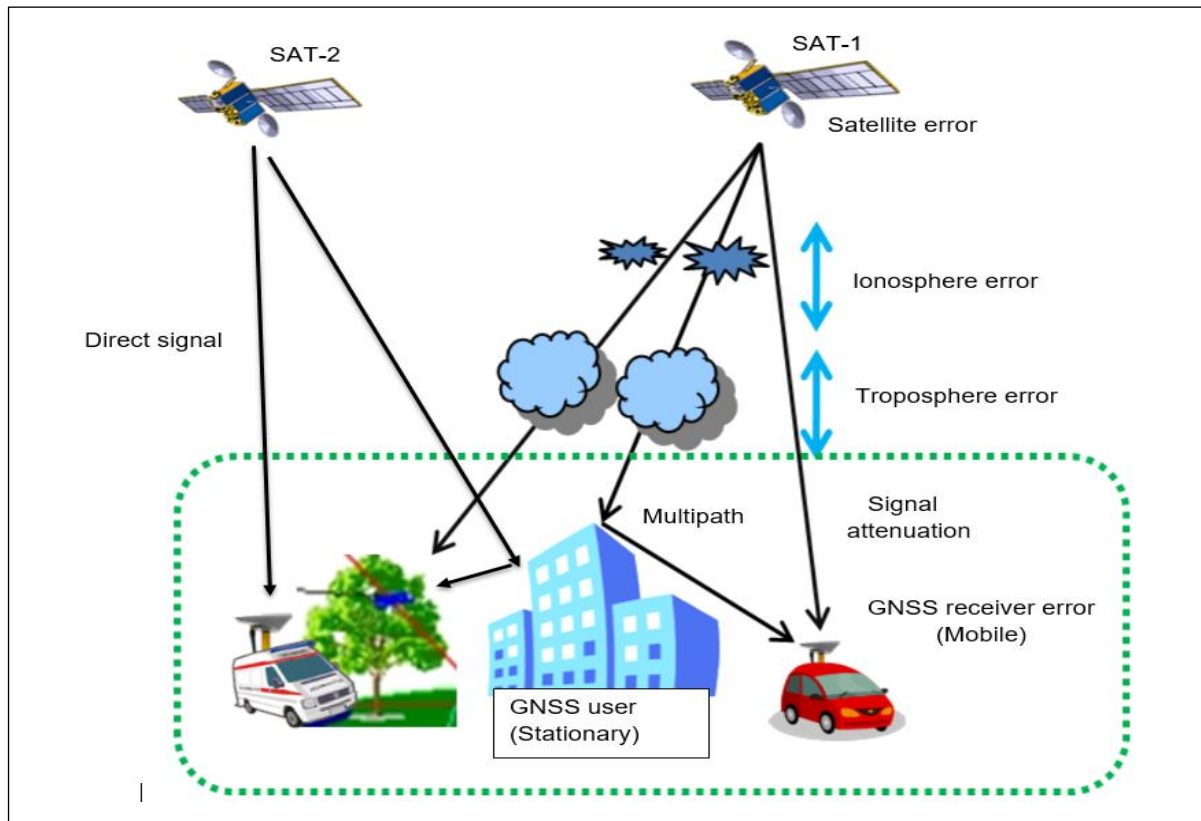


Figure 1.1: The causes of the signal degradation during the propagation.

The synchronization is currently a problem in the navigation scheme and is caused by the signal multipath and other relevant factors in the solar system. The satellite-based navigation system is carried out in an open-sky environment with numerous factors of the atmosphere involved [8]. Figure 1.1 illustrates the sources of signal multipath, attenuation, and other propagation errors in the interest of this research work for both fixed and mobile receivers. The signal multipath and attenuation along the satellite path are the points of interest for this research work because their impact can be mitigated at the user level. The signal multipath is the main source of signal errors in GNSS applications and is subject to the nature of the user's location. Urban areas are exposed to higher multipath errors compared to rural areas.

1.2. The GNSS synopsis

In this thesis, the first generation of the global navigation system is called GNSS1, and the second generation, a part of which is still under development, is called GNSS2. Currently there are two operating systems: the American Global Positioning System (GPS) and the Russian GLONASS. The first satellite-based navigation satellite was launched in 1970, and recent innovative technologies have enabled the world to devote radio wave communication to the sky or space [9, 10].

According to the recent studies, the currently used global navigation satellite system for both (GLONASS and GPS) and the anticipated GNSS2 share the identical operating ideologies and the procedures if observing their signal structure [11, 12]. Hence, both GLONASS and the GPS satellites are equipped to transmit the fundamental signals one or several adhering to Direct Sequence – Spectrum Signal (DS-SS) with the precise data called navigation message. The navigation message contains two segments: the location and the time of the mark found in the transmitted DS-SS signal. Most of the GNSS receivers obtain the distance approximation from the satellite using the calculated propagation delay of the specific direct signal and the final data on the user strongly depend upon the correctness of the propagation delay measurements [13, 14].

The relevant stakeholders approved the GPS in 1973, and the first satellite was launched in 1978. Many GPS-based satellites were launched into space, and by 1993, the GPS had 24 satellites in orbit, with a target of 33 satellites by then [15, 16]. The first aviation use of the GPS was declared in 1994. The recent demand for innovative navigation systems, as well as an incident involving poor navigation, have prompted plans to modernize the GPS; details can be found in [6, 16, 17]. The GPS Block IIR-M and IIF are designed and prepared to transmit the unencrypted L2 Civil Signal (L2CS) using the second carrier frequency link [18]. This will result in an easier and more consistent tracking of the transmitted signal [19]. Furthermore, the GPS has an additional signal called L5, and this is an open signal with a centre frequency of 1176.45 MHz [20]. The L5 frequency link is available on the GPS IIF and GPS III, respectively [21]. The inclusion of L2CS and L5 was intended to improve GNSS tracking of the carrier phase using the carrier to aid in ambiguity resolution for recent applications with the recent receiver adhering to the GPS satellite update [13, 14, 22].

The Russians followed the same approach to launch their spacecraft (COSMO1413) project called GLONASS in 1982. The GLONASS system was put into full operation in 1993. The GPS is better than the GLONASS in positioning applications, and the GLONASS is highly recommended in high-latitude areas. The GLONASS satellite constellation had at least 24 satellites. The GLONASS system is not fully operational, but it is linked to the GPS systems to improve precision. The augmentation for GPS and GLONASS was introduced to satisfy the necessities of accuracy and reliability for GNSS applications [23]. The augmentation programs were widely adopted and classified as the Local or Wide Area Augmentation System (LAAS, WASS) in the USA, EGNOS in European countries, and the Multi-functional Satellite Augmentation System (MSAS) in Japan [24]. The propagation delay of the GNSS signals and navigation data are usually obtained from three to four anonymous satellites to calculate the location coordinate, and one satellite is used for receiver clock error estimation with the triangulation procedure being used to compute the antenna location [22, 25]. However, there is only one signal that is able to propagate through the direct path to the receiver to calculate the required solutions.

1.3. The GNSS measurement and data modelling

The satellites for user measurements such as carrier phase and code have several supplementary time delays related to the signal propagation in the direct path. Furthermore, as shown in Figure 1.2, the clocks cause an additional time delay and geometric range between the user and the satellite. The nature of these delays is similar in the measurements for carrier and code [26]. The diverse delays are represented by the ionosphere refraction and the uncertainties that affect the range and existence of the carrier phase. Furthermore, there is a strong interaction between the satellite radio wave pattern and the peripatetic electrons in space, and the ionosphere refractive index is highly dependent on the frequency [27, 28]. The ionosphere is anticipated to be the dispersive medium for the radio wave pattern [29]. If the ionosphere is the dispersive medium, there are two velocities to be considered, the group and the phase velocity [30]. The phase velocity is referring to the phased broadcasting of the uniform wavelength for electromagnetic waves. The group velocity is the propagation of the wavelength in the form of groups at different frequencies.

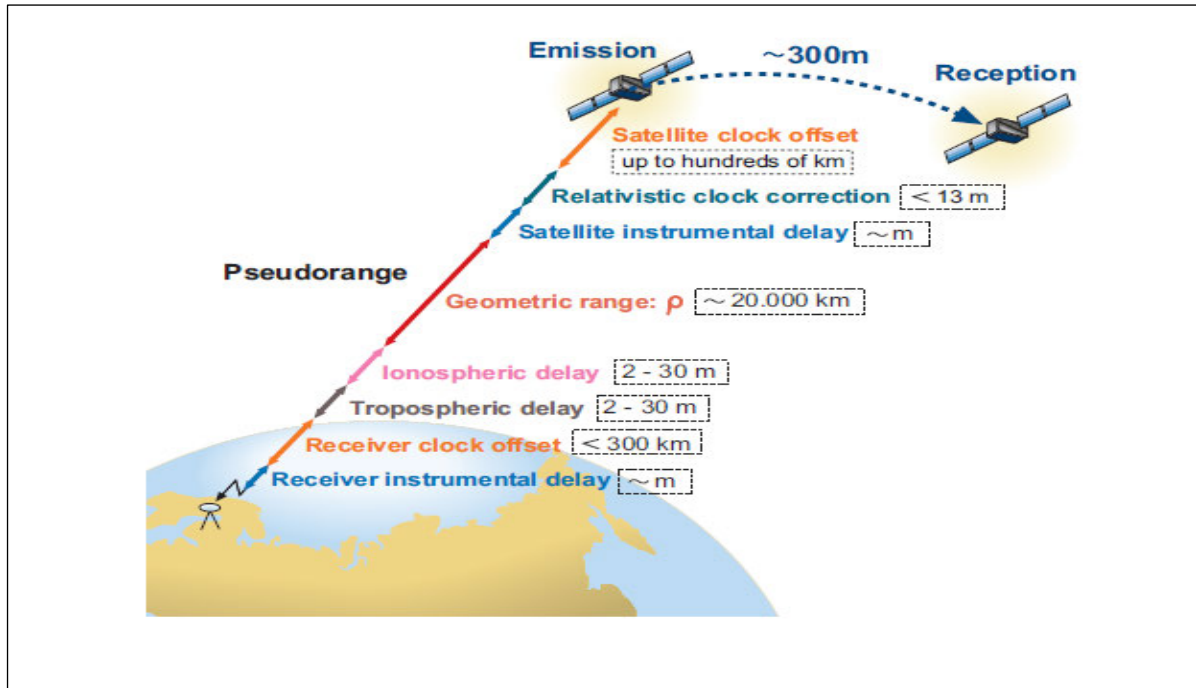


Figure 1.2: The pseudo-range measurements content[31].

There are two parameters to represent the signal propagation delay, the carrier phase and the complex envelope delay [32]. Hence, the signal processing unit integrated in the GNSS receiver has the vital duty to measure these binary parameters [33].

These are dual parameters, also called observables. Once the observables are processed, they are then transferred to the navigation data processor to complete the calculations of the time and location. The parameter of the complex signal that is fed to the navigation processor is $a_{CS}(t) = e^{-2\pi F_{CS}t}$, the scale of the light speed is δ_0 and is used to define and compare this signal to the proportionate signal that would turn out to be $a(t - \delta_0)e^{-2\pi F_{CS}\delta_0} e^{-2\pi F_{CS}t}$ if the propagation was assumed to be ideal, and the $a(t)$ is the pseudo-range time delay. With regard to the pseudo-ranges, the ranges measured differ from the real distance for the fixed applications because of the clock offset incorporated in the receiver, and the value of the δ_0 dignified from the phase term $e^{-2\pi F_{CS}\delta_0}$ of the received proportional signal is referred to as the carrier phase in this case [34]. This GNSS observable is quite accurate; it adds accuracy to the pseudo-range, and thermal noise is expected to produce an error of about 5 millimeters in GPS applications, which is deemed insignificant. The carrier phase and the pseudo-range are used in high-end receivers integrated with advanced signal processors. However, this does not completely insulate the GNSS receiver from the error that tends to degrade the accuracy of the navigation system [35].

The spread spectrum modulation provides an acceptable level of signal anti-jamming protection, and the received power is relatively low, at about -160 dBW for GPS applications. However, the GLONASS and GPS signals remain susceptible to the numerous sources of jammers. The GNSS residuals of the predicted and measured pseudo-range, carrier, and code comprise an approximate clock offset and the position error for the receiver. Furthermore, residuals are believed to also contain the measurement noise error, and these residuals are used as the input data for navigation. The satellite-based navigation uses radio beams that were invented a long time ago, around 1900. The following radio navigation systems were developed in accordance with all relevant spectrum requirements:

- The Transit system is known as the Navy Navigation Satellite System (NNSS). This radio wave system was designed to use the Doppler shift frequency to compute the receiver's location [36, 37].

The Transit system was developed between 1964 and 1996, since when the fixed or dynamic user has been able to compute the positions using the data signals from the satellite constellation [38].

- The Decca Navigation System (DNS): this system was mostly used in aviation and maritime applications. The user was computing their location by measuring the differential time between the transmitted and received signals [39]. The DNS is no longer in use as from 2000.
- Long Range Navigation (LORAN): This radio navigation system enabled the user to calculate its location by measuring the time differential between the receipt of the transmitted radio signals [40]. The results were represented in the hyperbolic graph to draw the line of position [41]. Satellite-based navigation, like other satellite applications, takes place in an open sky environment, and good line-of-sight (LOS) reception conditions and a large number of observable satellites distinguish such applications [42]. The satellite navigation system recitals are defined in terms of the following:
 - The integrity: This is defined as the reliability of the data supplied by the satellite navigation system to the GNSS receiver [43, 44].
 - Availability: This is referring to the availability of the navigation data to the user whenever it is required. The navigation data must be available continuously [45].

- Coverage: The GNSS signals emitted by the space satellite are adequate to precisely compute the location in this space volume [46].
- Accuracy: This is the level of conformance for the measured and calculated location for the user [47].

1.4. Problem statement and motivation

The use of GNSS for positioning, velocity, and time is becoming increasingly popular, and innovative GNSSs are critical for evolving and future GNSS applications. GNSS is capable of providing a wide range of services to both civilian and military applications worldwide. The performance of the GNSS in outdoor locations, especially in rural areas, is appealing. However, GNSS use has expanded into urban areas and indoor applications for both stationary and mobile users. The indoor and urban areas are considered to be challenging environments for GNSS applications. The buildings obstruct the GNSS signals in urban areas, and the walls or roof, as shown in Figure 1.3 masks indoor signals. In urban areas and indoor applications, GNSS accuracy and reliability are greatly reduced [48]. The GNSS architecture consists of three segments that are responsible for the complete processing of the GNSS signals, the space, control, and user segments [49]. The GNSS satellites generate and emit the satellites through the propagation channels to the user on the ground (e.g., car), in the air (e.g., aircraft), and on water (a ship or boat). The satellite generates the signal that contains a code phase and a carrier phase.

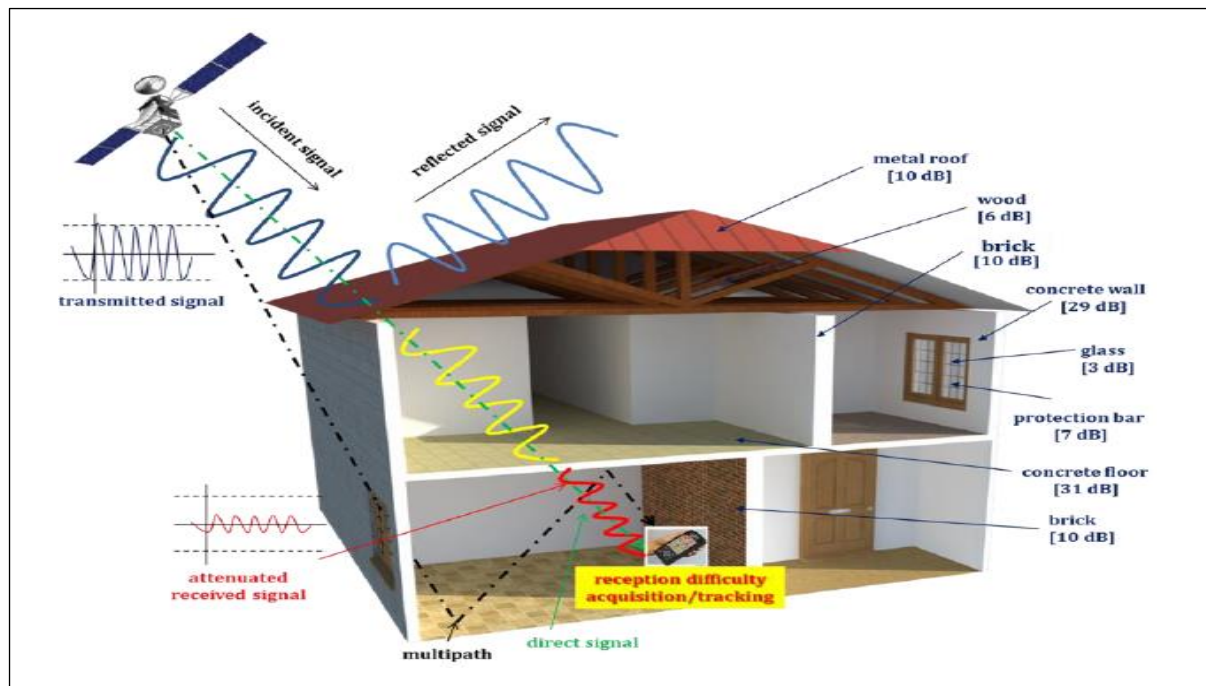


Figure 1.3: The indoor GNSS application and their power losses.

Figure 1.3 illustrate the power losses for GNSS indoor applications and the concrete floor is the major cause of the GNSS power losses followed by the concrete wall. Along the transmission of the signal to the receiver, numerous delays are anticipated, including the satellite clock offset, relative clock correction, satellite instrument delay, geometric range delay, ionospheric delay, tropospheric delay, receiver clock offset, and receiver instrument delay. These measurements in signal propagation from space to receiver are referred to as pseudorange and are depicted in detail in Figure 1.3. The movement of the generated signal waveform from the satellite to the receiver through the earth's layers is referred to as GNSS signal propagation [3]. The Earth layers impose serious threats to the signal waveform generated in space [4]. The GNSS multipath signal is the major contributor of signal distortion and poor signal strength in GNSS applications. Hence, the purpose of this research is to develop the numerical algorithms to estimate the existence of the multipath signal and further adopt the Collective Signal Detection (CSD) method to mitigate the impact of multipath signal.

1.5. The thesis objectives

There has been a remarkable development in the sphere of satellite navigation systems since the first threat to navigation data was experienced. The first American Navstar GPS unlocked the application for the market at large, and the Russians followed with a similar approach with their system, GLONASS. The imminent European Galileo is the topic of interest in this dissertation. The literature of this research incorporates numerous features of GNSS applications; however, numerous problems remain unresolved to some extent. As conferred above, this research proposes a user-based multipath mitigation technique that is flexible and based on the influence of the static or mobile user environment.

The signal to the GNSS receiver is obtained from space or air via the antenna for signal sampling and down conversion in order to perform dual signal processing, synchronization, and positioning in a sequential order. The multipath remains the leading cause of errors, this thesis proposes the use of GNSS multi-constellation and combined signal processing to address the common problem encountered by the GNSS receiver in its final stage of signal processing for synchronization and positioning. This will improve the signal strength and the reliability of GNSS applications. With all the motives being mentioned, the inclusive objectives of this research work are:

1. The main objective is to adopt Combined Signal Detection in multi-signal GNSS receivers to minimize the impact of signal multipath and attenuation along the satellite path.
2. Investigate the similarities between the GPS and Galileo baseband signals to justify the integration of these two systems in the process of adopting the CSD.
3. Study and analyse the concept of GNSS multi-constellation in order to support the adoption of the Combined Signal Detection
4. Investigate the sources of the signal degradation in GNSS receivers through an analysis of the effect of data bit transitions and the Doppler effect.
5. Evaluating the performance of Combined Signal Detection and further analysing the satellite availability in multi-signal GNSS applications
6. To investigate the detection of new multipath signals if using multi-signal GNSS receivers, and further derive the standard deviation of the covariance correlator output.

1.6. The thesis overview and arrangement

This thesis consists of seven chapters, with each chapter arranged to offer a perception of the actual content and intensity of the work carried out in this study. Each chapter also offers an insight on how the administrative objectives of this thesis are achieved. Chapter 2 provides an inclusive analysis of the global navigation satellite systems, the GNSS applications, and the description of the signal frequency bands and structures. A brief discussion of regional augmentation systems is provided, as well as the GNSS receiver's basic architecture and data processing techniques. Chapter 3 provides a comprehensive review of multipath propagation. This includes the discussion on the multipath detecting techniques, the monitoring techniques, the mitigating techniques, and the inclusive review of the multipath related information. In Chapter 4, the responsive concept of Combined Signal Detection (CSD) is introduced, tested, and analyzed using numerical algorithms. For the signal model that has been introduced, the front-end is presumed to be impeccably calibrated in relation to the appropriate standard; however, perfect calibration demands challenging technologies and computation, so the second version of the signal is also provided and is deemed to be amorphous.

The purpose of this approach is to analyze the arithmetical behavior of the multipath; this will further allow the removal of all undesirable signals through the exploitation of all possibilities provided by the CSD concept. In Chapter 5, the additional sources of the GNSS signal degradation are investigated. Most of the degradation sources in chapter five are resolved using differential methodologies, which are not possible with GNSS multipath signals. The collective description of the GNSS receiver is introduced in this chapter as an attempt to mitigate the signal multipath. In this way, the hybrid GNSS receiver is considered in the context of the GNSS multi-constellation to mitigate the multipath signal. This approach is intended to mitigate the impact of GNSS signal multipath. Chapter 6 analyzes the performance of the CSD methodology and the GNSS multi-constellation arrangements. Chapter 7 provides the conclusion of this study and the recommendations for future research regarding the CSD and multi-constellation methodologies to mitigate the GNSS signal multipath.

1.7 Publications and research outputs

The publications listed here, are provisions forming part of this research thesis with attendances in peer-reviewed conference proceedings and credited journals

Book chapters

1. **Bheki Madonsela**, Innocent Davidson, Chrispin Mulangu, The Analysis of Global Navigation Satellite Systems (GNSS) and the Numerical Estimation of Multipath Propagation. In: Bauk S., Ilčev S.D. (eds) The 1st International Conference on Maritime Education and Development. Chapter 39, pages 411-425, Springer, Cham. https://doi.org/10.1007/978-3-030-64088-0_39. 25 March 2021. ISBN 978-3-030-64087-3, Online ISBN 978-3-030-64088-0.
2. **Bheki Madonsela**, Innocent Davidson and Crispin Mulangu, "Integrating DNP3 Devices into IEC61850 Server". *Interdisciplinary Journal of Economics and Business Law*, Vol. 8, Special Issue 2019, pp. 264-285. ISSN (Online): 2047-8755

Peer-reviewed conference proceedings

1. **Bheki Madonsela**; Innocent Davidson, and Emmanuel Mukubwa, "The Use of the Carrier to Noise Ratios (C/N₀) to Alleviate the Problematic GNSS Phase Multipath". In *Proceedings of 2022 30th Southern African Universities Power Engineering Conference (SAUPEC)*, Durban International Convention Centre, Durban, South Africa, 25-27 January 2022, DOI: 10.1109/SAUPEC55179.2022.9730774

2. **Bheki Madonsela**; Innocent Davidson; Chrispin Mulangu, “The Influence of the Signal Distorsions on the Satellite Based Navigation Systems”. *Proceedings of 2021 Southern African Universities Power Engineering Conference/Robotics and Mechatronics/Pattern Recognition Association of South Africa*, Potchefstroom, South Africa, 27-29 Jan. 2021, doi : 10.1109/SAUPEC/RobMech/PRASA52254.2021.9377223

Journals articles: (Under review)

1. Bheki Madonsela; Innocent Davidson, Emmanuel Mukubwa: Evaluating and Quantifying the Performances of the GNSS Signal Acquisition Techniques. **MDPI**
2. Bheki Madonsela; Innocent Davidson, Emmanuel Mukubwa; Analyzing the ML-Based Algorithms for GNSS Data Bit Synchronization and Decoding. **MDPI**

1.8. The Contribution of the study

The following are the innovative contributions found in this research work to the current body of knowledge regarding GNSS applications and operational architectures:

1. The second chapter provides a comprehensive review of GNSS architecture, GNSS frequencies, and widely available civil GNSS constellations.
2. In chapter four, the concept of combined signal detection is proposed as the function of Doppler frequency and GNSS code phase for all visible satellites. Furthermore, there are six steps that are proposed to assist with the implementation of the combined signal detection.
3. Developed a procedure for detecting new or additional multipath signals in the event that the previous estimation was erroneous. The procedure to detect the new path is further used to evaluate the performance of the combined signal detection.
4. GNSS plays crucial role in economic development in applications such as: agricultural production, utility industries, logistics, emergency services and leisure. Hence, an improvement to the concept of GNSS technologies will increase the efficiency of above mentioned applications of which they are key drivers of economic growth and sustainability.

CHAPTER TWO

Literature review

In chapter two, the state of art of the GNSS is discussed. The satellite constellations, their signal structures and frequency bands are comprehensively discussed.

2.1. Background

The general concept of identifying the appropriate systems that allow the calculation of the position using the satellite constellation is called Global Navigation Satellite Systems (GNSS). As stated in Chapter 1, there are two well-known GNSS networks that existed long ago: the American GPS and the Russian GLONASS. Numerous research projects are being carried out to improve the GPS's worldwide coverage and effectiveness. Not so long ago, two GNSS networks were developed, the European Galileo and the Chinese BeiDou, which are referred to as the GNSS 2 [50]. The GPS and Galileo are using the same operating principle, where the measured distance between the user and the set of observable satellites is used to calculate the position of the user by estimating the propagation time of the emitted signals.

These signals are from each of the space satellites to reach the end user and evolve around the appropriate time synchronization of devices. The synchronization of devices is the most important aspect when dealing with positioning systems. The content of this chapter will present the theoretical background based on the ground satellite receivers, including a comprehensive description of the signals emitted by the satellite and the deviations that they go through just before reaching the ground-receiving antenna. The focus will be on the signal processing tasks that are performed by the system receivers such as time delay estimation, carrier stage, and received signal Doppler shift. The comprehensive literature regarding the GNSS provided in this chapter adheres to the objectives of the thesis.

2.2. The Satellite communication procedure

The basic and early generation structure of the satellite is made up of the following units: the satellite bus section, crosslink antenna, solar panel array, gate away antenna, battery and radiator, communication section, and the satellite payload [51]. Amongst these units, there are two that are most essential: the satellite bus unit and payload unit, respectively. However, for profound missions, there may be a supplementary service support unit [52]. The satellite bus units contain all necessary support functions for the satellites. Namely:

- The Telemetry, Tracking, and Control (TT&C) RF link
- The Guidance Navigation and Control (GNC) systems, which are integrated with the On-Board Computer (OBC),
- The propulsion, including the fuel tanks and the thrusters
- The Attitude Orbit Control System (AOCS)

The payload units of the satellites provide the personalized payload for its operation. In many cases, the payload of the satellites is in the form of processing transponders.



Figure 2.1: The satellite structures[31].

The transponders receive the appropriate signal through the feeder link or either uplink and further rebroadcast the signal at the different frequencies available in the network using the user link or the downlink [53]. The satellite's processing transponders could decode and recode its messages before the message was retransmitted [54]. The generic satellite communication systems consist of three main parts: the control segment, ground segment, and space segment. The control segment refers to the ground satellite that is fitted and equipped with devices to control and monitor the satellite, and the "space" segment refers to the satellites located in the orbit for communication [55]. Within these spheres of arrangement, there are three vital components of a communication link to allow the exchange of data between the divisions of the communication system that include the receiver, transmitter, and the physical gap between them [56]. The elementary relationship is shown in Figure 2.2 below.

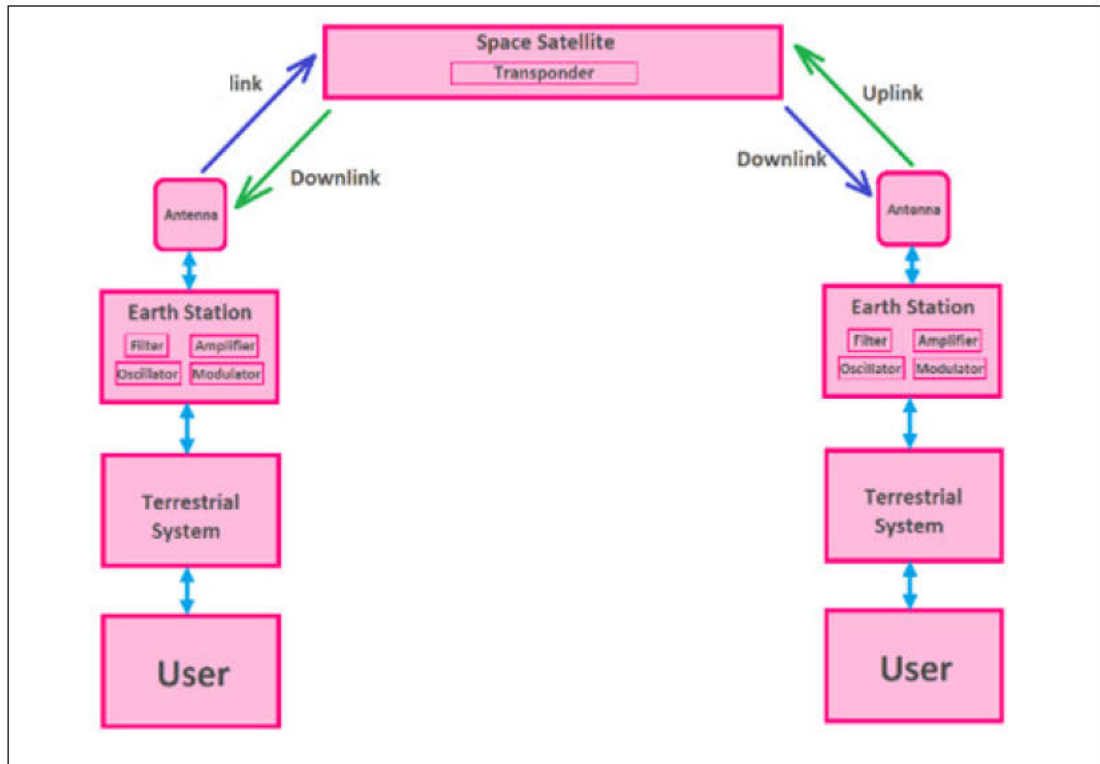


Figure 2.2: The concept of satellite communication[57].

The uplink is used for the information that is transmitted from earth transmitting station to satellite, whereas downlink is the path to transmit the information from the satellite to earth receiving station [58].

2.3. The GNSS architecture

The GNSS is the collective and generic term that defines the concept of satellite-based navigation systems that are used to obtain the position required by the user over the globe [59]. Three segments complete the GNSS architecture (the space, control, and user segments). The space segment is made up of the space satellite that is responsible for the signal transmission [60]. The control segment is made up of appropriate control centres to ensure adequate functioning of the entire navigation system [61, 62]. Lastly, the user segment includes the GNSS receiver that uses the information obtained from other satellites to compute the position [63].

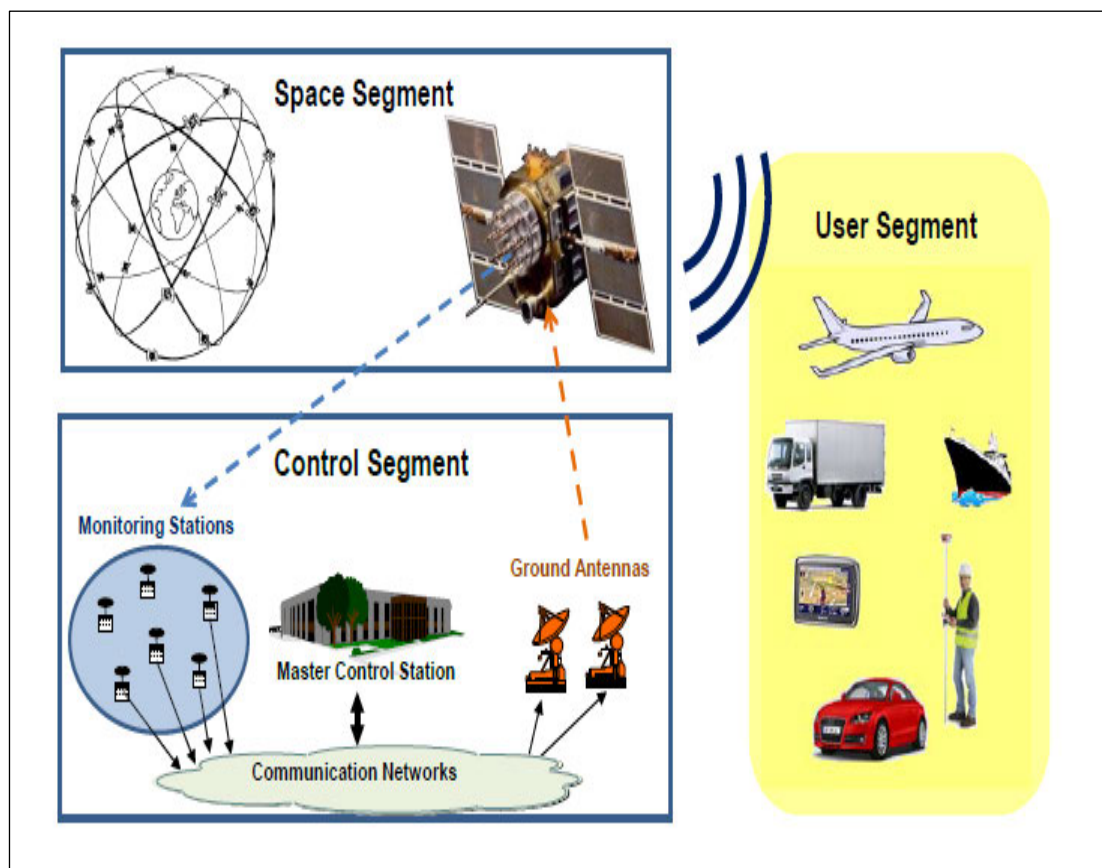


Figure 2.3: The architecture of GNSS systems [64].

This architecture is used to separate the responsibility of each segment from the next. Here in Figure 2.3, it is shown that the key purpose of the space segment is to generate and emit carrier and code signals over the open space of the earth. The space is also able to broadcast and store the navigation data message uploaded by the ground segment. The extremely stable atomic clock integrated into the satellite controls and administers signal transmission, and the space must have a sufficient satellite constellation to ensure that at least three to four satellites are simultaneously observable from any point on Earth [65]. Each satellite constellation has a dedicated control segment to perform a similar function in a different way [66]. The control segments are used to update the navigation-related messages in all satellites, use the satellite integrated atomic clock to maintain the GNSS time scale, preserve the configurations and the statuses of the satellite constellations, and envisage the satellite clock evolution and related ephemeris [67]. The control segment of the GPS is represented in Figure 2.4, the Glonass in Figure 2.5, and the Galileo in Figure 2.6.

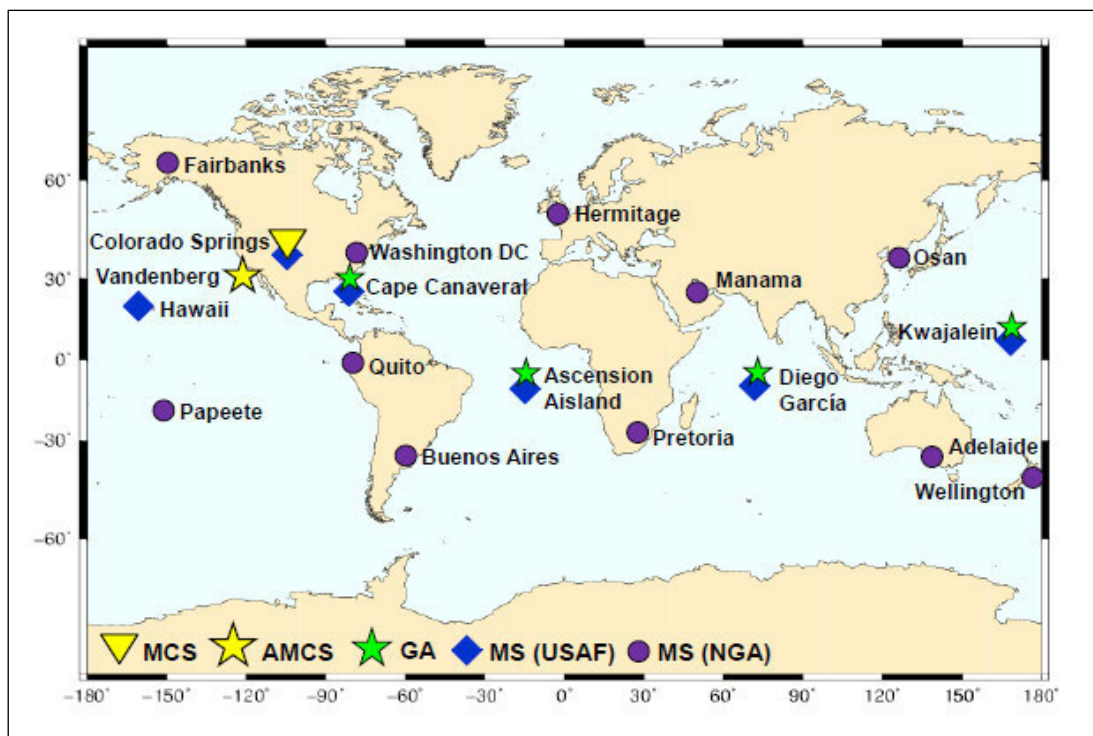


Figure 2.4: The control segment of the GPS [68].

The ground or control segment of the GPS is made up of five comparative stations in the ground: the Master Control Station (MCS), the alternative Master Control Station (AMCS), and the Ground Antennas (GA) [69]. the Monitoring Stations from the United States Air Force (MS-USAF) and the Monitoring Stations from the National Geospatial-Intelligence Agency (MS-NGA). The data being collected across the globe is sent to the MCS to estimate satellite orbits, clock errors, and generate the navigation-related message after an advanced processing step [70].

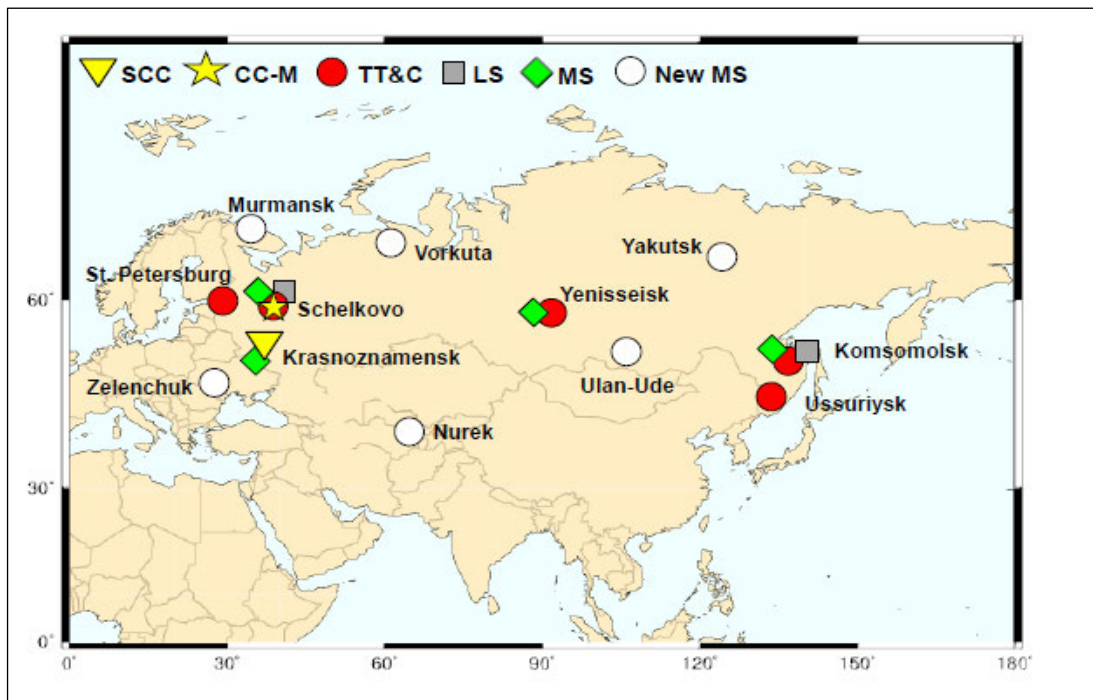


Figure 2.5: The Glonass control segment [71].

The infrastructure of the Glonass controls segment is made up of the following stations: the System Control Centre (SCC), the Centre (SCC), Central Synchronizer (CC-M), the Telemetry, Tracking and Control (TT&C), the Laser Station (LS) and the Monitoring Stations (MS) [71].

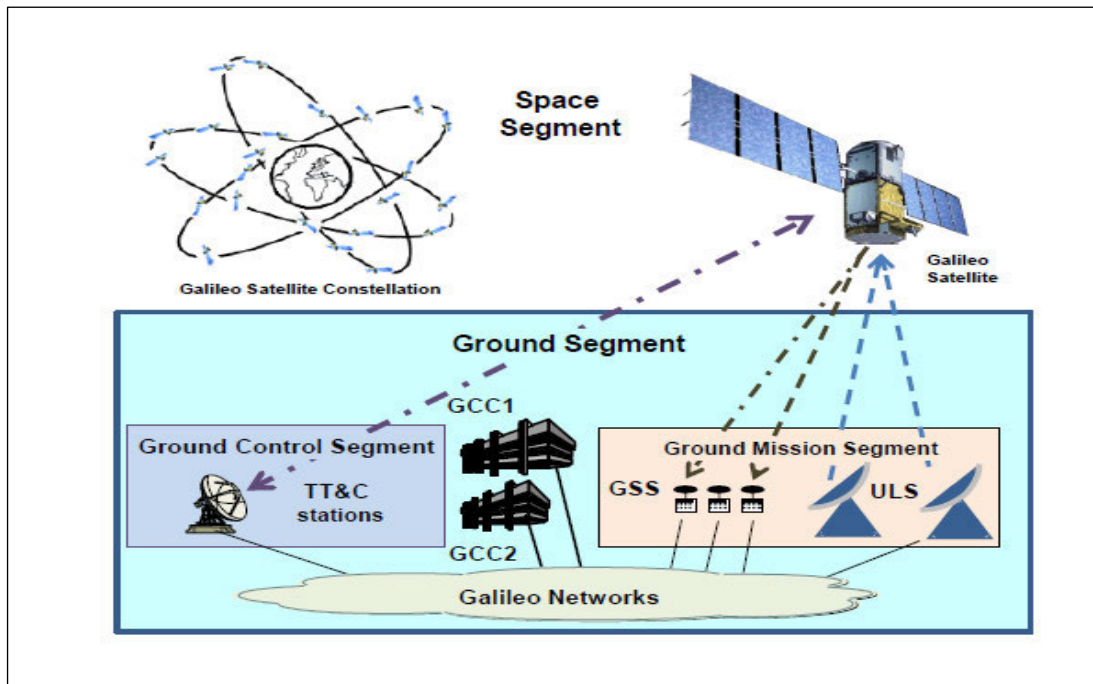


Figure 2.6: The Galileo ground segment [72].

The ground segment for the Galileo is different from the GPS and Glonass control segments. The Galileo control segment is designed to provide the hybrid communication network to interrelate the Ground Control Centre (GCC) with the Uplink Stations (ULS), Galileo Sensor Stations (GSS), and the Telemetry, Tracking, and Control units (TTC) [73]. The last integrated segment in the global navigation systems is the user segment, which is composed of the GNSS receiver. The main function of the user segment is to receive the GNSS signals from all the observable satellites to determine the pseudorange and use the navigation equations to calculate the user's locations and provide the precise time [74]. The GNSS receiver is made up of the microprocessor, radio frequency unit, time precision oscillator, data feeding source, and data memory unit. The antenna plays a crucial role in the accuracy of the calculated position [75]. The GNSS satellites are continuously transmitting the navigation signal at higher frequencies assigned to those satellite constellations. The user will use that data to compute the location [76]. The transmitted signal contains the navigation information and the range codes, and the three components of the signal, also known as the PRN sequences, are explained as follows:

- Navigation data is a binary code message that provides data on the satellite orbit, such as satellite position, velocity, and health status [77].
- Ranging code: Once the zero and one sequence is reached, the receiving equipment will calculate the radio signal's travel time from the satellite to the user [78].
- Carrier: This is the sinusoidal waveform of the radio frequency at any frequency level.
- The ground system's architecture may differ from one another. However, the basic architecture must include the devices required to connect the space segment and the ground segment networks [78].

The ground segment is referring to any user or facility at the ground level, which includes vessels, vehicles, aircraft, and stationary buildings that are fitted with antennas to receive the signals.

2.4. The GNSS frequency distribution

The GNSS uses different frequencies based on their constellations, and the frequency bands are distributed along the spectral density and satellite constellations [79]. The GNSS users must fall into the prescribed frequency bands. The radio frequency spectrum is shared amongst numerous services such as cell phones, microwaves, radar satellites, televisions, and radios [26]. The spectral frequency has two major frequency bands, the Radio Navigation Satellite Services (RNSS) and the Aeronautical Radio Navigation Services (ARNS) [80]. The ARNS have two bands, the lower and upper bands, as shown in Figure 2.7.

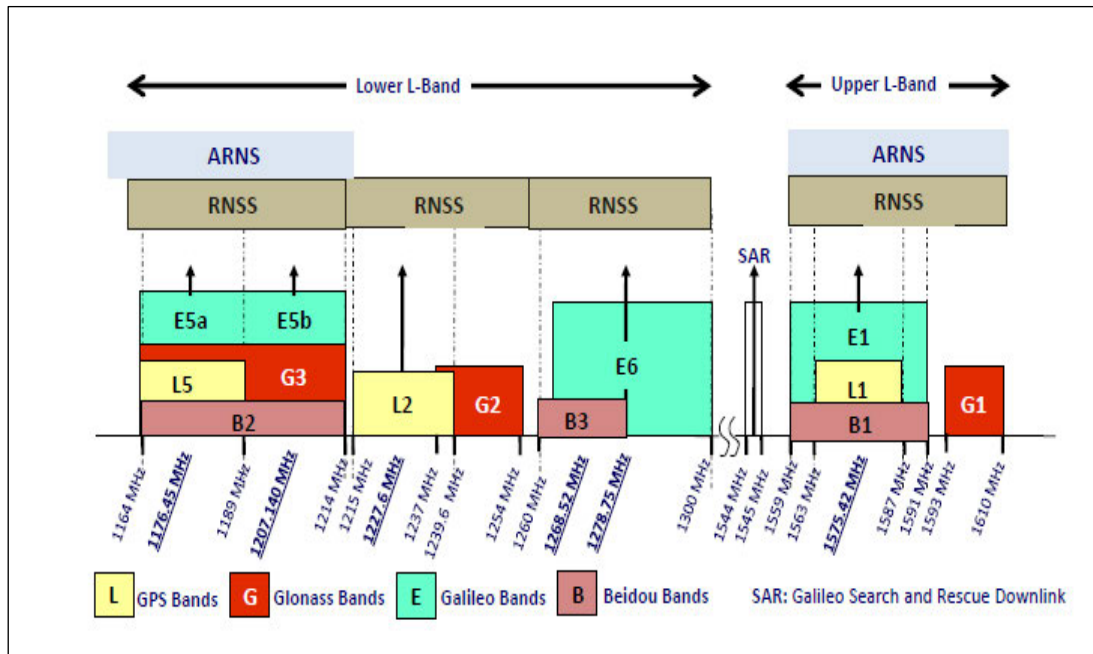


Figure 2.7: The GNSS frequency bands [80].

From Figure 2.7, it is shown that the GPS L1, GLONASS G1, BeiDou B1, and Galileo E1 fall within the upper band of the electromagnetic spectrum. [19]. In applications where high accuracy and reliability are required, the GPS L1 and L2 frequency bands are used. The GPS L1 and L2 have the capability of removing uncertainties causing the ionospheric errors.

The GPS frequency links shown in Figure 2.7 have the following characteristics

- GPS L5: The signal emitted from this frequency link have higher chip rate and improved abilities to handle the multipath in challenging environments compared to GPS L1 link [81].
- GPS L2: This frequency link has the longer code phase and improved correlation functions. These abilities are required in locations where the coverage of the GPS is poor and the signal weak such as indoor and urban area applications [82].

The GNSS signals in RNSS and ground radar are more vulnerable to the signal interference to the similar extent of the upper and lower bands frequencies [83].

2.5. The GNSS spectrum signal structure

In this section, the GNSS baseband signal is introduced. The operating principles of both Galileo and the GPS are comparable and are grounded in the concept of direct sequence spread spectrum (DSSS) signal transmission [84]. With the numerous satellites being observable to the user, Code Division Multiple Access (CDMA) transmission is enabled for the signals to involve two sets of crucial components [85]. These components, the signal ranging code, also known as the pseudo-random noise (PRN) spreading sequential code, and the data link, considered to be at the low rate used to transmit the appropriate information regarding the positioning. The arithmetic representation of the composite baseband signal model being transmitted by the x^{th} satellite is expressed as following.

$$S_{T,x}(t) = S_{I,x}(t) + js_{Q,x}(t) \quad (2.1)$$

Equation 2.1 contains the real part as the phase waveform, or sine waveform, and the imaginary part as the quadrature, as the cosine waveform. For simplicity and for further analysis, this is expanded as follows:

$$\begin{aligned} S_{I,x}(t) &= \sqrt{2P_I} q_{I,x}(t) \\ (2.2) \end{aligned}$$

$$= \sum_{m_I=-\infty}^{\infty} d_{I,x}(m_I) \sum_{u_I=1}^{N_{C_I}} \sum_{k_I=1}^{L_{C_I}} c_{I,x}(k_I) g_I(t - m_I T_{bI} - u_I T_{PRN_I} - k_I T_{C_I}) \quad (2.3)$$

$$\begin{aligned} s_{Q,x}(t) &= \sqrt{2P_Q} q_{Q,x}(t) \\ (2.4) \end{aligned}$$

$$= \sum_{m_I=-\infty}^{\infty} d_{Q,x}(m_Q) \sum_{u_Q=1}^{N_{C_Q}} \sum_{k_Q=1}^{L_{C_Q}} c_{Q,x}(k_Q) g_Q(t - m_Q T_{bQ} - u_Q T_{PRN_Q} - k_Q T_{C_Q}) \quad (2.5)$$

where the:

- P_I represents the transmitted power that deemed to be equal for observable satellites.
- $d_{I,x}(t)$ is the low-rate data bit sequence that is between $[-1, 1]$ of the bit period T_{bI}

- $c_{I,x}(t)$ represent the sequence of the PRN distribution along with the chip length L_{C_I} and the chip period N_{C_I} that is ranging in between $[-1, 1]$.
- g_I this is the shaping pulse

The general description of the function above includes both the in-phase signal component and the quadrature signal component. The transmitted power must be controlled monitored by inserting the $\delta = 1$, hence, the elements of the new equation will be:

$$p_I(t) = \sum_{u=0}^{N_{C_I}-1} q_I(t - uT_{PRN_I}) \quad (2.6)$$

$$p_I(t) = \sum_{k=0}^{L_{C_I}-1} c_I(k) g_{T,I}(t - kT_{C_I}) \quad (2.7)$$

$$S_{TR} = \sqrt{P_{Total}} \left(\delta \sum_{m=-\infty}^{\infty} d_I(m) p_I(t - mT_{bI}) + j\sqrt{1 - \delta^2} \sum_{n=-\infty}^{\infty} d_Q(n) p_Q(t - nT_{bQ}) \right) \quad (2.8)$$

The DSSS signal transmission is condensed and compared to the BPSK modulation as it is possible with GPS systems, the element to control the spectral power is $\delta = \frac{1}{\sqrt{2}}$ and for the simply pattern the total transmitted power will be $P_{Total} = 1$. Furthermore, the $L_{C_Q} = L_{C_I}$, $N_{C_Q} = N_{C_I}$, $T_{bI} = T_{bQ}$

$$S_{T,BPSK} = \frac{1}{\sqrt{2}} \sum_{m_I=-\infty}^{\infty} d_{I,x}(m_I) \sum_{u=1}^{N_{C_I}-1} \sum_{k=0}^{L_{C_I}-1} c_{I,x}(k_I) g_T(t - kT_c - mT_b - uT_{PRN}) \quad (2.9)$$

$$S_{T,BPSK} = \frac{1}{\sqrt{2}} \sum_{m_I=-\infty}^{\infty} d_{I,x}(m) p(t - mT_b) \quad (2.10)$$

The signals are transmitted to reach the user through the radio wave propagation channel and the propagation channel modifies the original signal amplitude $a_{x,m}(t)$, delay $\tau_{x,m}(t)$ and phase $\theta_{x,m}(t)$, in many applications with the multipath being considered. The nearby ground objects are anticipated to reflect the GNSS signals in many applications, therefore more than one signal will reach the receivers antenna coming through the different paths [86, 87]. The activities of the propagation channels are monitored and modeled using the impulse response of the linear time variable channel with the additional multipath (M) signal to the direct signal [88]. The propagation channel to model and monitor the multipath is:

$$p_{x,m}^{Channel} = \sum_{m=0}^{M-1} a_{x,m}(t) e^{j\theta_{x,m}(t)} \delta(t - \tau_{x,m}(t)) \quad (2.11)$$

2.6. Global Navigation Satellite Systems (GNSS)

constellations

This section presents first GNSS constellation that is fully operational and the second generation of the GNSS satellite constellation that is still under development [89]. There are four satellite constellations represented, two for GNSS1 (the first generation) and two for GNSS2 (the second generation). There are four satellite constellations represented, two for GNSS1 (the first generation) and two for GNSS2 (the second generation).

Table 2-1: The summary GNSS1 constellation

Title	Traditional GNS Generation	
The 1 st GNSS	GLONASS (Russia)	GPS (US)
Number of satellites	24	24
Satellites types	LEO	LEO
inclination orbit	64,8°	55°
Altitude of the satellites	19,100 km	20,200 km
Frequency Bands and Modulation	L1=1602/L2=1246 MHz BPSK/FDMA	L1 = 1575.42/L2 = 1227.6 MHz QPSK/CDMA
Codes and signal characteristics	SP (standard precise code) HP (high precise code) Repetition of HP = 1week Repetition of SP = 1ms Chipping rate of HP = 10.23 Mb/s Chipping rate of SP = 1.023 Mb/s	C/A (code) P (precise code) Repetition of C/A = 1ms Repetition of P = 1week Chipping rate of P = 10.23 Mb/s Chipping rate of C/A = 1.023 Mb/s
Period of circulation	11,15 hours	11,58 hours
Accuracy (Vertical and horizontal speed)	Horizontal (SP) = 5-10 m Vertical = 15 m Velocity vector = 10 m/s	Horizontal (C/A) = 5-10 m Vertical = 15 m Velocity vector = 10 m/s

Table 2-1 above represents the first generation of GNSS, denoted by GNSS1, and the second generation of GNSS (GNSS2) was recently launched and is expected to be fully completed in the nearest future. The GNSS2 (Compass or BeiDou and European Galileo spacecraft) are not fully completed yet; hence the characteristics comparison can be drawn as following in Table 2-2. Lately, the GNSS systems are gradually becoming more important globally because of their huge influence on economic growth. GNSS also acts as a synchronizing system for accurate time measurements; however, the GNSS systems do not carry out the navigation task directly. The purpose of the GNSS systems is to define the position of the receiver within the specific coordinate system at a specific time.

Table 2-2: The summary GNSS2 constellation

Title	Recent GNSS Generation	
The 2 nd GNSS	BeiDou (China)	Galileo (Europe)
Number of satellites	35	30
Satellites types	27 MEO/5 GEO/3 IGSO	30 MEO
Frequency Bands and Modulation	E2 = 1561/E2 = 1589 MHz E6 = 1268/E5b = 1207 MHz QPSK and BPSK/CDMA	E5a = 1176.45/E5b = 1207.14 MHz E5(E5a+ E5b) = 1207.14 MHz E6 = 1278.75/E1 = 1575.42 MHz BPSK and BPSK(m)/CDMA
Accuracy (Vertical and horizontal speed)	Horizontal (C/A) = 3 - 5 m Vertical = 3 - 5 m	Horizontal (SP) = 4 - 5 m Vertical = 4 - 5 m

The GPS satellite calculates the information relating to the location by ensuring that all satellites visible from the line of sight have a similar time [34]. This is attained by adhering to the reference common stratum (sequence 1) timing. Furthermore, the positions of all satellites are known; hence, the ground station receiver subtracts the signal transmission time. (That is encoded to the transmitted signal) (T_{ST}) from the signal arrival time (T_{SA}) . The time difference can be then used to calculate the pseudo-range (P_R) to the satellite using the following expression.

$$P_R = T_{SA} - T_{ST} \quad (2.12)$$

The geometrical modelling of four or more of these measurements allows the calculation of the receiver's location and further allows the time error estimation at the receiver. The Navstar GPS is using the Low Earth Orbit (LEO) satellites.

2.7. The GPS spreading code and signal structure

Three Right Hand Circularly Polarized (RHCP) radio frequency links are used to integrate the GPS space segment into the GPS navigation system. Those frequency links are L1, L2, and the envisaged link, which is L5 [90]. The inclusion of the third frequency link is to achieve faster data acquisition for all kinematic positioning applications and improve data response compared to double band frequencies [91]. The frequencies for the L-band class need one or more-bit trains for modulation, where each bit train is formed by modulo-2 supplementing the pseudo-random noise (PRN) code [92, 93]. In this case, the system for downlink data is called navigation data, or NAV data. Previously, the GPS used to transmit signals on dual radio frequencies in the L bands known as Link 1 and Link 2, respectively. Both links are derivatives of the fundamental frequency of the $f_0 = 10.23$ MHz. There are two services used in GPS system.

- The Standard Positioning Services (SPS) – this GPS open service used globally and is free of charge denoted by the single frequency in the L1 frequency band [94].
- The Precise Positioning Service (PPS) – this is the restricted service preserved for military use [95]. PPS is using both L1 and L2 respectively and uses the CDMA to transmit the diverse signal on the similar radio frequency based on BPSK [96].

The GPS systems were later modernized to include the supplementary link 5 in the frequency band and new ranging codes of the diverse frequencies. Those codes are L2C, L5C and L1C and M code for military [97, 98].

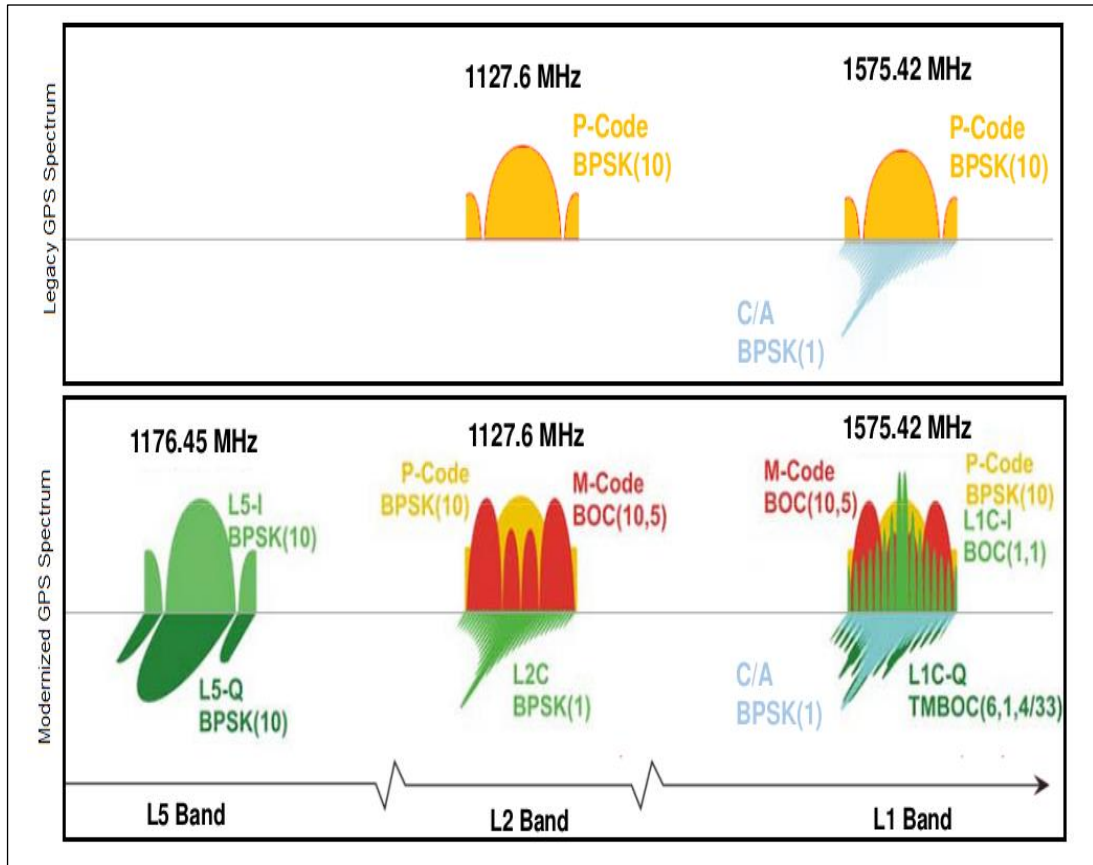


Figure 2.8: The Legacy and modified GPS frequency bands [99].

Figure 2.8; represent the traditional and modernized GPS frequency bands with the inclusion of L5 and the modulating scheme. According to [100], the PRN codes, also known as the gold codes, were selected for this application because they have the required properties that include simplicity of implementation and cross-correlation. Hence, the GPS receiver is designed and equipped to perform the correlation to extract the timing of the signal and further recover the Navstar GPS satellite data. Sometimes, the receiver has many satellites in view; in that case, all visible satellites must be separated to perform unique data recovery and timing. Hence, the system will then reject the demands for self-interferences for the spectrum spreading codes with upper and lower cross-correlation. It must be noted that the gold codes or PRN codes are linear combinations of two maximum length sequences (M-sequences) having different offsets [101].

The gold codes have autocorrelation and cross-correlation of the following values: $[-1, -x_1(m), x_2(m), -2]$, and the following mathematical expression is developed.

$$x_{1,2}(t) = \begin{cases} 2^{\frac{m+1}{2}} + 1 \\ 2^{\frac{m+2}{2}} + 1 \end{cases} \quad (2.13)$$

$2^{\frac{m+1}{2}} + 1$, in this case, the m code is the odd number

$2^{\frac{m+2}{2}} + 1$, in this case, the m code is even number

This expression shows that, the generation of the gold codes is comparatively simple, the gold codes is made up of modulo-2 sum with two Linear Feedback Shift Register (LFSR) outputs and the feedback are defined as the polynomial feedback [102]. Following are the forthcoming and currently used Navstar GPS spectrum spreading codes: For GPS L1 at the carrier frequency of: 1 575.420 MHz.

2.7.1. The C/A spectrum code

This is the PRN C/A code that is used for Space Vehicle (SV) number estimated to be one (1) millisecond length with the chip rate of 1023Kbps and their pattern are linear [103]. They are generated by modulo-2 that is having dual subsequences called G1 and G2 respectively. The G1 and G2 sequential functions are generated by 10 – multistage LFSR referring to the following polynomial arithmetic that is adhering to the concept of the shift register [104].

$$G1: 1 + y^3 + y^{10} \quad (2.14)$$

$$G2: 1 + y^2 + y^3 + y^6 + y^8 + y^9 + y^{10} \quad (2.15)$$

2.7.2. The P spectrum code

This is the PRN P code that is used to denote the SV number that is seven (7) days in length with the chip rate of 10.23 Mbps and their dual subsequences are referred as X1 and X2, respectively. The length of X1 is 15, 345, 000 chips and X2 is 15,345,037 chips, respectively. Both subsequences are generated by modulo-2 sum with 12 – stage records where are reduced to: $X1 = 4092$ and $X2 = 4093$ chips. P code is also modulated on L2 frequency bands at BPSK (10) and 50 bps data rate for military use.

$$X1: 1 + y^6 + y^8 + y^{11} + y^{12} \quad (2.16)$$

$$X_2: 1 + y + y^2 + y^5 + y^8 + y^9 + y^{10} + y^{11} + y^{12} \quad (2.17)$$

2.7.3. The Y spectrum code

The physiognomie of code Y is widely available despite the fact that it's include the possible jammer that will generate the signal with the intension of imitating the GPS signal and causes the receiver to receive the wrong signal along the satellite path [104]. Hence, the P code has been encrypted by a secured Y code to ensure that the jammers cannot generate Y replica code [105].

2.7.4. The L1C code

This is made up of (L1C- I data) and (L1C-Q pilot) PRN codes. Both data and pilot are using the MBOC (6.1.1/11) modulation type at the chip rate of 1.023 Mcps and the data rate of 50 bps [97, 106]. This is preserved for civilian use. For GPS L2 at the carrier frequency of: 1 227.600 MHz

2.7.5. The L2CM code

This is the PRN L2 Civil Moderate (CV) code with the SV number that is 20 milliseconds in length and the chip rate of 511.5Kbps. L2CM establish the short cycle linear pattern of 10,230 chips [107, 108].

2.7.6. The L2 CL code

This is the PRN Civil Long (CL) code and the SV ranging number of 1.5 second in length. The chip rate of L2 CL code is 511.5Kps and it does generate the polynomial function with the count of 767,250 chips [109].

2.7.7. The M codes

This is the Military (M) code signal that is anticipated to provide the improved jamming resistance when compared to code Y signal [110]. M code is enabled to transmit the power at higher levels without interfering with Y code or C/A code receivers and further provide the security in terms of privacy, exclusivity and authentication for military [111]. The M code consist of the binary offset signal having the spreading code of 5.115 Mbps and the frequency of 10.23MHz, represented as BOC (10.23,5.115) modulation and BOC (10,5) modulation respectively [112]. For GPS L5 at the carrier frequency of: 1 176.450 MHz

2.7.8. The L5 code

This is the PRN code also known as the quadrature phase code (represented as Q-5 code) and the PRN in – phase code (represented as I - 5 code) with

the SV number of one (1) millisecond in length. The chip rate is 10.23Mbps and modulated by BPSK (10) [113].

2.7.8. The Non-standardized code

These codes are available to protect navigation user from receiving and utilizing the abnormal navigation signal. Resulting from the malfunctioning of the SV generating system.

2.8. The Glonass satellites constellation

The Glonass GNSS is a navigational satellite system that provides real-time position as well as velocity [37]. Glonass is a Russian-owned satellite that is similar to the Navstar GPS. The Glonass has 24 satellites in orbit and is enabled to be used by civilian and military users on different frequency band levels. The payload of the Glonass is using the Direct Sequence Spread Spectrum (DSSS) signals and the Binary Phase Shift Keying (BPSK) modulation, which are very comparable to the Navstar GPS payload operation.

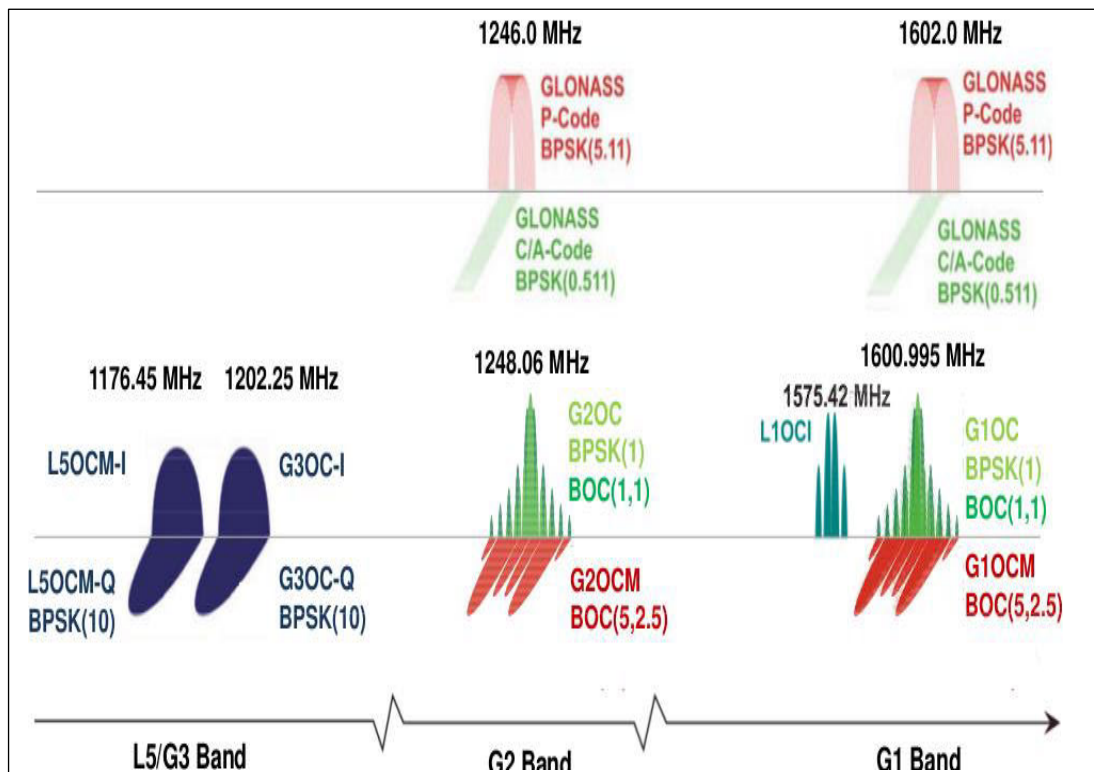


Figure 2.9: The Glonass frequency bands [114].

The legacy Glonass signals are G1 band and G2 that is right hand circularly and both centered in the L band of the dual radio frequency [115].

The modernizations of the Glonass systems include adding the additional third band G3 to the ARNS and the use of CDMA signal transmission, as well as the third band for all three bands. The G3 signal will provide the dual codes, the third civilian code, and the military codes, which are modulated into these frequencies together with the navigation message adhering to the BPSK modulating method [116]. The civilian code and the military code have 1 ms and 1 s periods, 586.7 m and 58.67 m of chip width, which means they are more time-sensitive than GPS signals. For that reason, the GPS is widely used compared to the GLONASS system [117].

2.9. The Galileo spreading code and signal structure

The Galileo Navigation Satellite is intended to transmit a variety of signals via Right Hand Circularly Polarized (RHCP) frequency links. Galileo uses Binary Offset Carrier (BOC) for modulation similar to the M- code of the GPS. Following are the sets of Galileo signals with frequency ranges: E5, ranging between 1215 and 1300 MHz; E6, ranging between 1599 and 1610 MHz; E2-L1-E1, also called L1 [90, 91]. The product of a BOC-modulated signal has two significant components: Unfiltered PRN code with a chip rate and values estimated to be [1], and an unfiltered signal with a frequency equal to or much higher than the chip rate and acting as a signal carrier [118].

The Galileo payload is nearly identical to that of the Navstar and US GPS. However, it has two significant changes: the first is that the modulation and frequencies are well designed to avoid signal interference with the Navstar GPS already in orbit, and secondly, the Galileo uses the pre-computed feedback codes also known as a memory codes [119]. Those memory codes are generated by gold codes using the hereditary numerical procedure of the Medium Earth Orbit (MEO) [120]. Each Galileo satellite in space is capable of transmitting 10 navigation signals along the frequency bands E1, E6, E5a, and E5b. These frequency bands are all right-handed, circularly polarized, and are intended to support Galileo services for diverse users [121].

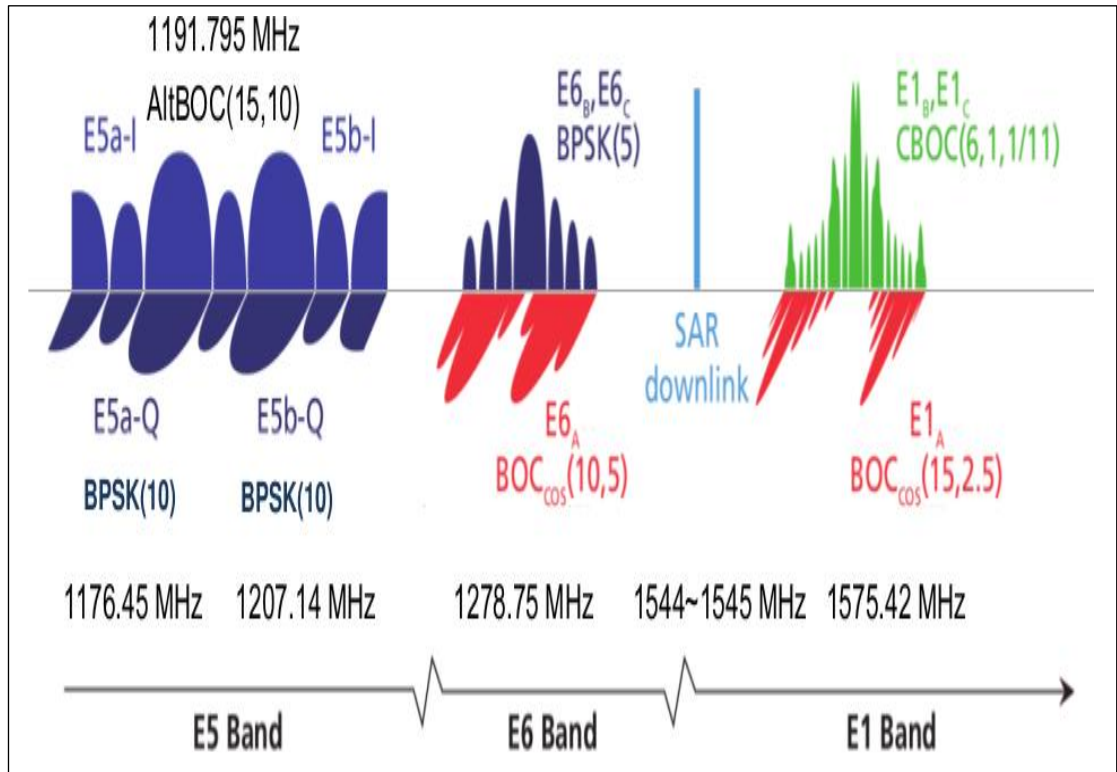


Figure 2.10: The Galileo frequency bands [99].

All satellites are sharing the similar frequencies; the signals are distinguished by the CDMA methods being used per system [122].

2.9.1 The Galileo E1

GalileoE1 signal stream or data is mainly modulated by means of the CBOC (6, 1, 1/11+) modulation techniques with the pilot bit stream being modulated using CBOC (6, 1, 1, /11-) inflection. The CBOC (6, 1, 1/11) is the combination of BOC (6, 1) and BOC (1, 1). Hence, the autocorrelation model of the GalileoE1 baseband signal is provided as well [123].

2.9.2 The Galileo E5 and GPS L5

The civil aviation users are authorized to use L5 as an additional ARNS frequency band. Therefore, the use of dual frequency bands L1 and L5, respectively, will allow the estimation of the ionosphere delay for airborne applications, since the ionosphere delay is the foremost error that interrupts the pseudo-range measurements [124]. Both Galileo E5a and GPS L5 are sharing the same frequency bands, and the identical GNSS antennas are used to process the signal for both GPS L5 and Galileo E5a [125].

The complexity of the GNSS network has been improved by utilizing the GPS L5 and Galileo E5a on similar platforms. The Galileo E5 band is made up of E5a and E5b, respectively. The E5a supports the Galileo Open Service (OS), which is said to be free to users worldwide. The signals being transmitted in the E5a band are called open access signals [126]. They include two main components: the E5a-I data channel and the E5a-Q pilot channel. The E5a is used to transmit basic data that provides support for the timing and navigation messages at a low speed of 25 bps. The E5a frequency band is shared with the GPS L5, as stated above. The E5b frequency band supports the Galileo OS and the Commercial Services (CS) [127]. The transmitted signal contains the E5b-I data stream and the E5b pilot stream at a data rate of 125 bps. The E5b frequency band is shared with the Chinese BeiDou B2b and the Glonass G3. Both E5a and E5b are unified and modulated together to form one broad signal, E5, at the carrier frequency of 1191.795 MHz using the Alternate Binary Offset Carrier (AltBOC) modulation [126, 128].

2.9.3 Galileo E6

The E6 frequency bands is exclusively committed the CS and the Public Regulated Services (PRS). The PRS is used by the security authority such as police and, military and is controlled by the government [129]. E6 is capable of providing three components in the navigational signal, the E6- A that is only available to the authorized PRS users of the state and is encrypted form of signal, the E6 – B is the CS signal that represents data stream and the E6 –C also the CS used signal that represent the pilot stream [130]. The data transmission rate of the E6 band is 500 bps and is widely shared with BeiDou B3.

2.10. The BeiDou satellite constellation

China owns the BeiDou satellite constellation, also known as the Compass. BeiDou is a recently developed navigational satellite similar to Galileo in terms of being a part of GNSS 2 [131]. The BeiDou's basic architecture and design differ significantly from the architectures of Glonass, Galileo, and Navstar GPS.

The BeiDou necessitates the dual communications link to broadcast the signal and is intended to use MEO and Geosynchronous Earth Orbit (GEO) satellites [89, 132]. It has the additional satellites of the Inclined Geosynchronous Orbit (IGSO). This navigation satellite uses innovative techniques for exchanging information with the central server as explained in [133], and this is called common view.

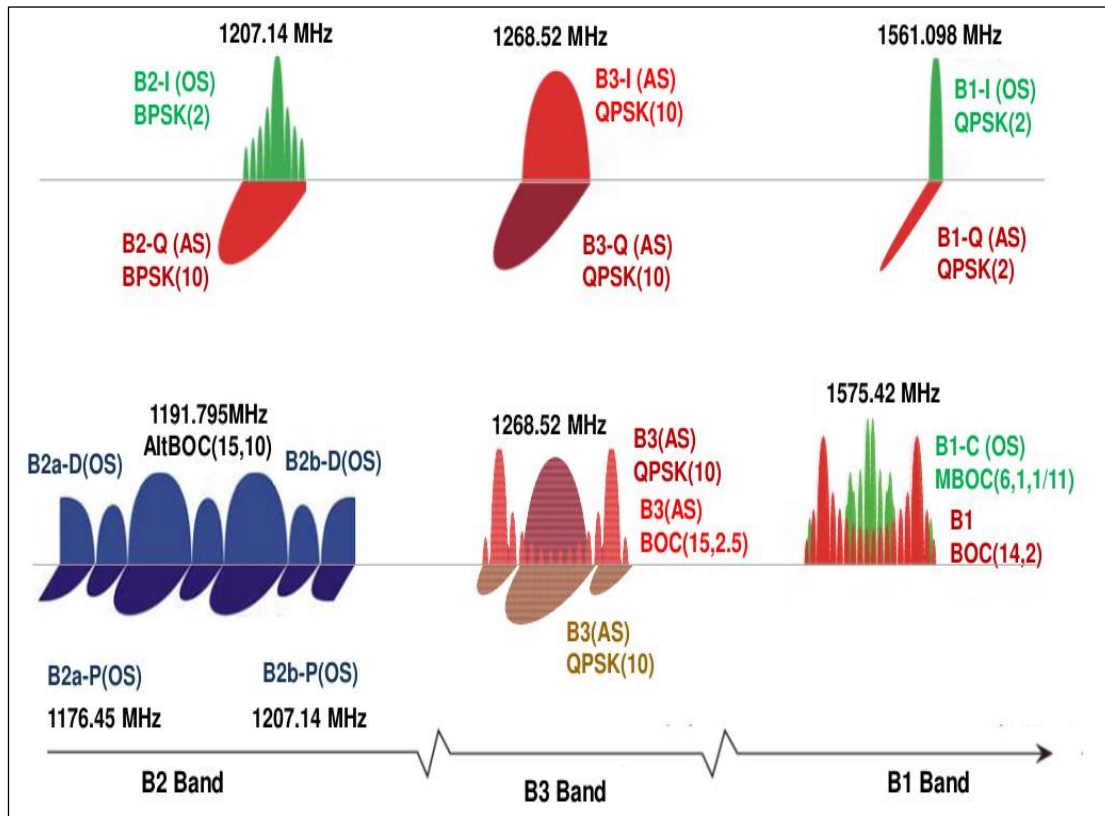


Figure 2.11: The BeiDou frequency bands [99].

The BeiDou satellites transmit right hand circularly polarized signals all centered at the L bands of the three radio frequencies known as B1, B2 and B3 and shown in Figure 2.11 and Table 2-3. There is represented in terms of phase II and III. Phase II represent the regional services and the phase III represent the global services [134]. Table 2-3 summarizes the phase III.

Table 2-3: The 3rd phase of BeiDou signals and constellation.

Band	Carrier Freq. (MHz)	PRN Codes	Modulating Scheme	Code Chip rate (Mcps)
B-1	1575.42	B1	BOC (14.2)	2.046
		B1- C_D	MBOC (6.1.1/11)	1.023
		B1- C_P		
B-2	1191.795	B2 – a_D	AltBOC (15.10)	10.23
		B2 – a_P		
		B2 – b_D		
		B2 – b_P		
B-3	1268.52	B3	QPSK (10)	10.23
		BE- A_D	BOC (15,5.5)	2.5575
		BE- A_P		

2.11. The Generation and broadcasting of the satellite signals

Figures 2.12 and 2.13 are used to illustrate the signal transmission and modulation hardware of the GPS adhering to L1 and L5 frequencies, respectively. There are similarities between these two hardware systems, such as the low rate of navigational data (50 bps) modulated to the coded spectrum signal and further modulated into L-band (1-2 GHz) stage carriers [93, 135]. However, there are differences between these two signals listed as follows:

- The rating code of the spread spectrum signal is 1.023 Mbps, particularly for L1, which represents a civil signal, whereas the rating code for the L5 signal is 10.23 Mbps, sometimes even 10 times higher than the L1 spectrum code rate.

- L1 frequency signal is normally transmitted at a frequency of 1.57542 GHz, and the L5 signal is transmitted at a frequency of 1.17645 GHz, respectively.

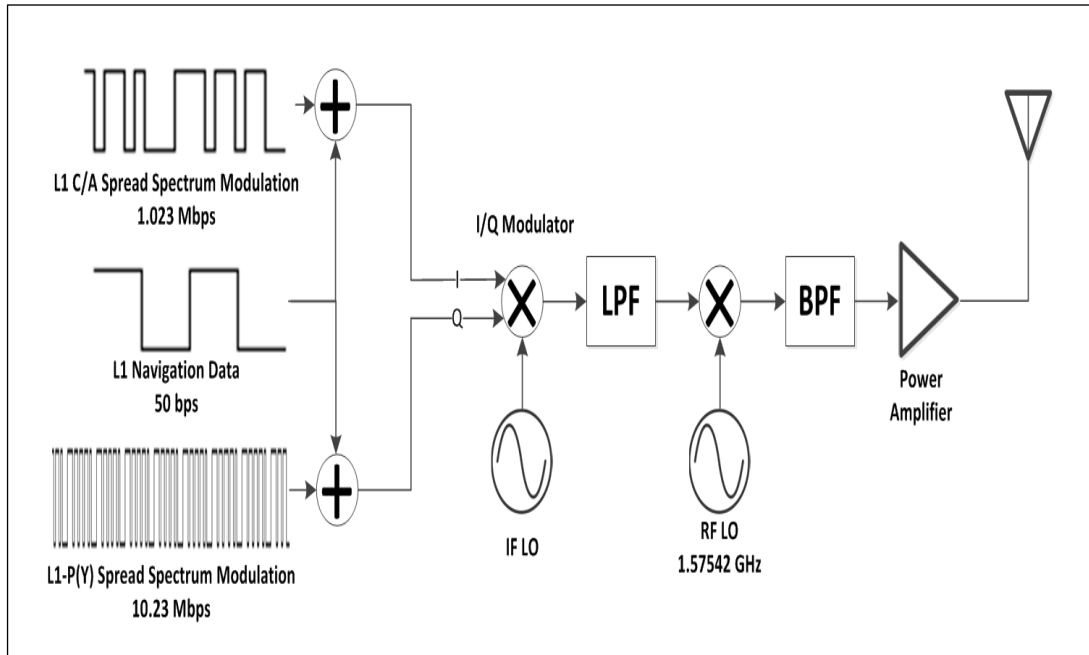


Figure 2.12: The Intonation and Broadcast of the GPS signal through L1 Frequency link [136].

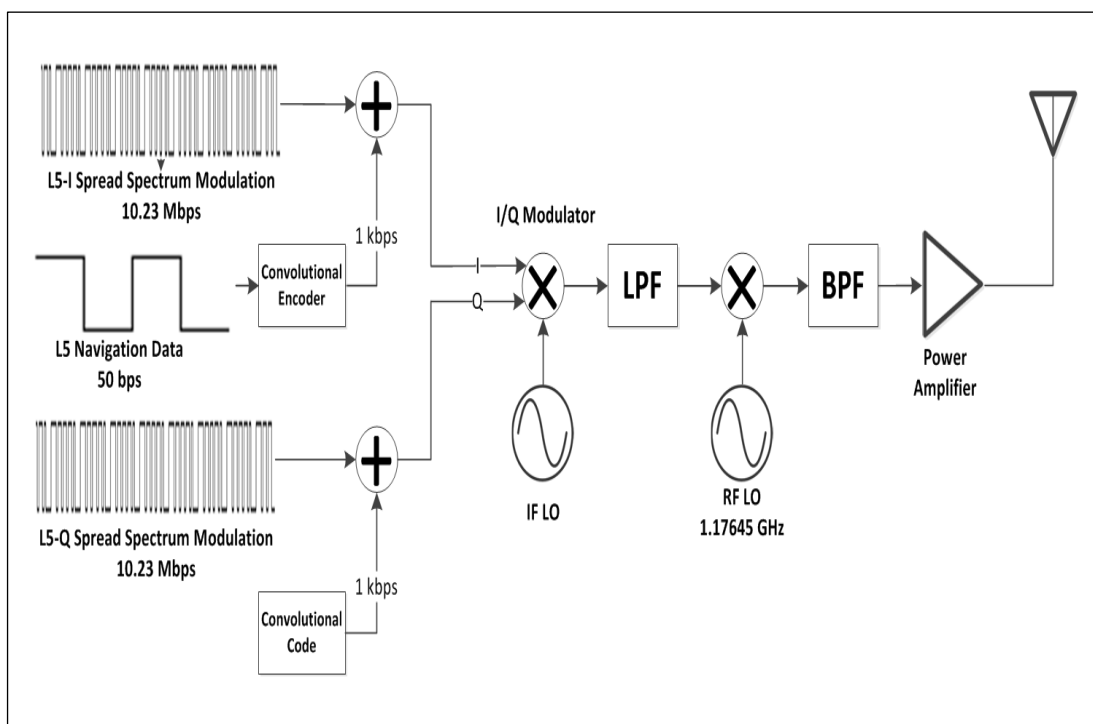


Figure 2.13: The Intonation and Broadcast of the GPS signal through L5 Frequency link [136].

For modulation, the L-1 frequency band or C/A spread spectrum code generator was developed in such a manner that it will only use two 10-bit Linear Feedback Shift Registers (LFSRs), and the outputs are added to the modulo-2 of the system [137]. Both shifts must register a similar maximum length that has the precise code period of 1023 chips. The consequential spectrum code for the signal is also called "gold codes." They are normally clocked at a speed of 1.023 Mbps, and the recurrence occurs every millisecond. The frequency of the L5 spread spectrum coded generator is designed to use two 13-bit LFSRs, and the outputs are generally added to modulo 2, similar to the L1 frequency band [138]. L5 is capable of generating the maximum length, which is 8192 bits. Once the 8192 bits have passed, the spread-spectrum code will repeat itself to generate the 10.230 chips, and then the code will be clocked at a speed of 10.23 Mbps and repeat in every 10.230 bit.

2.12. Navigation frequencies and spectral density

The frequency spectrum of the transmitted GPS signal at the L1 band is illustrated in Figure 2.14 and Figure 2.15 correspondingly. The L1 frequency is 1575.42 MHz and the L5 transmitting frequency is 1176.45 MHz separately.

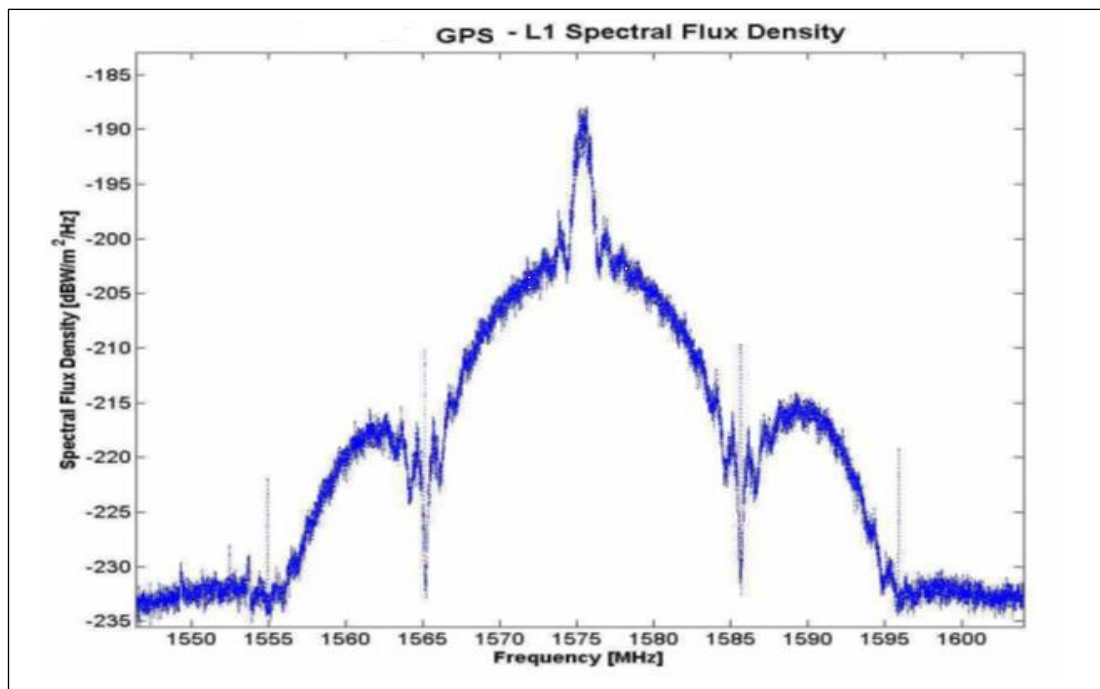


Figure 2.14: The illustration of the GPS L1 centre frequency [139].

As witnessed in figure 2.14, the frequency spectrum of L1 has the centralized frequency value of 1575.42 MHz, the spectrum code representing civil has the chip rate of 1.023 Mchips per second, and the outcome is the narrow frequency value of 2 MHz [140]. The widespread band of 20 MHz around the centre is also observed.

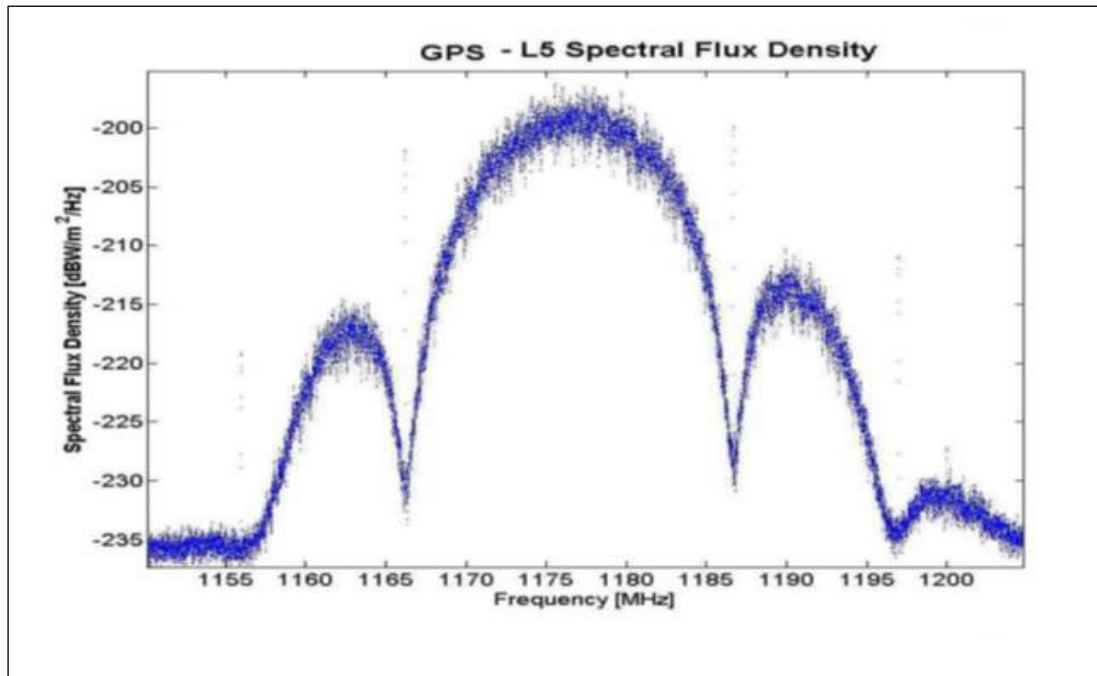


Figure 2.15: The illustration of the GPS L5 centre frequency [139].

The illustration of the L5 frequency spectrum is represented in Figure 2.17, and the spectrum has the frequency of 1176.45 MHz as the center frequency with the singlewide band spread of 20 MHz [141]. However, the spread spectrum code for civil is causing the chip rate to be 10.23 Mchips per second, which is more than 10 times higher than the civil spectrum code for L1 [142]. The good news is that even with 10-fold increases in chip rate, the system remains operational, as navigational performance improves with an estimated value of three (3).

2.13. The signal processing and receiver design

The receiver is integrated with the signal processor to perform the pivotal function of reconstructing the carriers and further extracting the codes and messages for navigation purposes [143].

Once this is done, the signal receiver then performs the Doppler shift measurements by equating the received signal and the signal generated by the user receiver [144] . Because the spacecraft satellite is in motion, the received navigational signal will certainly be Doppler shifted, and furthermore, the code ranges are determined by the Delay Lock Loop (DLL) using the correlation code [145]. The receiver's future in the future GNSS network must support both frequencies, GLONASS and GPS, as well as tracking the various GNSS signals. There is a strong need of adopting the hybrid GNSS receiver as shown in Figure 2.16. This will assist in adopting the wide and collective signal processing in GNSS receiver.

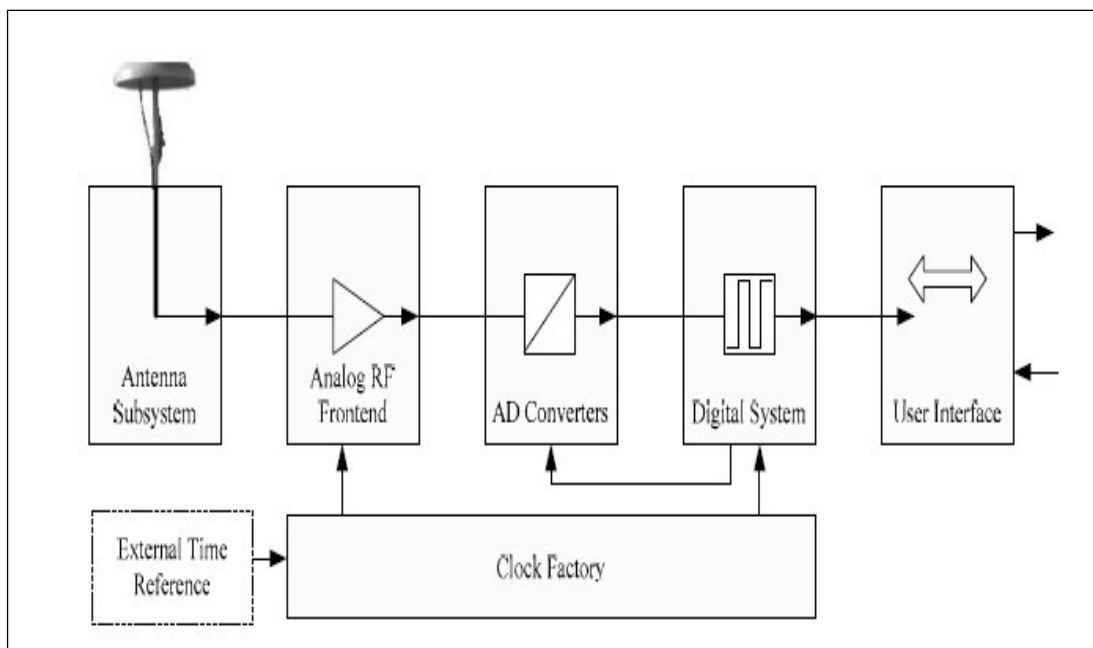


Figure 2.16. The basic architecture of Hybrid Galileo/GPS Receiver Concept.

Figure 2.16 above shows the collective components of the hybrid GNSS receiver (GPS/Galileo). The signal receiver performs the essential de-spreading of the signal codes to all visible satellites once the sampling and Analog to Digital Conversion (ADC) are completed in the originally received signal. The current designs of GPS receivers involve the integration of the digital components as illustrated above. The Right Hand Circularly Polarized (RHCP) antenna, with hemispherical signal coverage gain, is the first and most important component of the signal receiver. The RHCP antenna is used to receive the radio signals for the navigation messages from all satellites that are available [146, 147].

The RHCP antenna can be used in conjunction with the navigation nomenclature, called Line-of-Sight Signals (LOSS). The most popular types of antennas are low-profile with micro-strip and helix elements [148]. The utilization of the antenna arrays and the procedure of exploiting their spatial varieties in terms of tracking, detecting, and positioning is the foremost theme of this research work. The Low Noise Amplifier (LNA) is the significant element that is used to block the noise carried in by the RF signal collected by the antenna [149]. Furthermore, LNA is also used as the filter that shapes the received signal code and minimizes out-of-band RF signal interference [150]. The most popular and commercial receivers are normally equipped with a 2 MHz bandwidth filter for C/A L1 code, and the satellites are described to have the highest filter of 20 MHz for the transmission stage [151]. The higher-performing receivers usually exploit the system configurations and need to be provided with a wider bandwidth to allow for better synchronization and wider bands since they have a very sharp signal pulse. However, the wider bandwidth allows the additional noise to pass through a filter or LNA. The noise level in the power is estimated using the following expression:

$$P_{NL} = kT_E B_w \quad (2.18)$$

Where:

- k is the Boltzmann's constant ($K = 1.3806 \times 10^{-23} \text{ JK}^{-1}$)
- T_E represent the effective noise temperature in Kelvin (K), the GPS uses ($T_E = 513 \text{ K}$)
- B_w is denoting the bandwidth in Hertz (Hz)

Consequently, when designing the navigation receiver, the LAN bandwidth is the foremost requirement. The typical gain values to be incorporated when designing the LAN filter are between 20 and 40 dB, with the noise value of the amplifier ranging from 3 to 4 dB. Hence, the ratio of signal to noise is computed at this stage. The Navstar GPS C/A code is reported to have the capability of transmitting 478.63W of Effective Isotropic Radiated Power (EIRP). The losses due to propagation are estimated using the following expression:

$$\text{The factor for the free space loss } (F_{\text{FSL}}) = \left(\frac{\alpha}{4\pi r}\right)^2 \quad (2.19)$$

Where:

- $\alpha = \frac{c}{f_{l,1}} = 0.19 \text{ m}$ if using the wavelength carrier and
- $r = 2 \times 10^7 \text{ m}$ the considered average distance between transmitter and receiver.

The results will be:

$$F_{\text{FSL}} = \left(\frac{0.19}{4\pi \times 2 \times 10^7}\right)^2 = -182.4 \text{ dB}$$

The results are being influenced by the atmospheric attenuation value of (-2 dB) and the assumption that the bandwidth receiver have 2 MHz. Therefore, the SNR for C/A code is given by:

$$\text{SNR}_{\text{C/A code}} = (S_{\text{p dB}}) - (N_{\text{p dB}}) \quad (2.20)$$

Equation (2.20) is expanded to:

$$\begin{aligned} &= (P_{\text{TX}}) - F_{\text{FSL}} + (A_{\text{AT}}) - P_{\text{N}} \\ &= 26.8 + (-182.4) + (-2) - (-138.5) \\ &= -19.1 \text{ dB} \end{aligned} \quad (2.21)$$

where:

- $S_{\text{p dB}}$ is the decibel signal power
- $N_{\text{p dB}}$ is the decibel noise power
- P_{TX} is the transmitted power
- A_{AT} is the signal attenuation along atmospheric layers

From these results, it can be realized that, the GPS signal is entirely suppressed by the thermal noise. The equation (2.20) assumes that the signal is synchronized by frequency. As the results the Doppler shift and the carrier frequency of the received signal is removed by the digital or analog techniques. From the analysis of the data transmitted by the satellite, the baseband signal is expressed with the following signal parameters, the generic data sequence (d), periodic chip code (c), the chip pulse function(δ_y), the chipping period (T_c), full code number in the bit (N_c) and the data period (T_b).

$$S_0(t) = \alpha_0 \sum_{m=-\infty}^{\infty} d(m) \sum_{u=0}^{N_c-1} 1 \sum_{k=0}^{L_c-1} p(t) \delta_y(t - \tau_0 - xT_c - uT_{PRN} - mT_b) + x(t) \quad (2.22)$$

$$S_0(t) = \alpha_0 \sum_{m=-\infty}^{\infty} d(m) \dot{g}(t - \tau_0) + x(t) \quad (2.23)$$

Where the (δ_y) function represents the transmitted signal pulse that filtered by the pre- correlation filter and the $x(t)$ function is the thermal noise. The main objective of the system synchronization for the GNSS network is to estimate the time deferral (τ_0) together with the embedded information of the carrier phase (θ_0) in the amplitude of the phase complex. Both Galileo and GPS signals are sum of data component, excluding the GPS L1C/A. For each component the signal waveform, are collective and they form the resultant signal that is further reproduced by the system Radio Frequency (RF) carrier and the final combination of the waveform called baseband signal is formed. The baseband signal is likely to be centralized about the carrier frequency due to the modulation of the waveform by the RF carrier system. The modulation of the waveforms by the RF carrier leads to center the signal about the carrier frequency.

2.13.1. The digital processing of the GNSS signal on the GNSS receiver

The GNSS baseband signal shown in equation (2.21) is captured by the receiving antenna in analog form. The signal is filtered and converted into digital format [152]. In digital processing, there are three main steps to processing the signal: the signal acquisition, the signal tracking, and the signal modulation [153]. The main aim of the signal acquisition and tracking is to evaluate the parameters of the incoming signal such as the carrier phase, code delay and Doppler shift. The estimation of the Doppler shift, code delay, and carrier phase strongly depend upon the correlation process.

2.13.2. Correlation process

The core of signal processing in GNSS receivers is GNSS signal correlation. The models of the correlator outputs are given by the GNSS vendor to ease the configuration of the GNSS receiver [154].

As a result, the GNSS signal's correlation function is first prompted along the analogue unit of the GNSS receiver. Following is the list of properties for the GNSS signal correlation function.

- The baseband signal filter is located in the receiving antenna's output and is fed as an input to the GNSS receiver's RF front end.
- The comprehensive correlation in the GNSS receiver: the GPS L1 C/A, the GPS L5 and Galileo E5a baseband signals are having the local replicas generated locally within the GNSS receiver with similar modulation scheme. The autocorrelation is used to estimate the correlation function of the receiver [155].
- The prototype of correlator output for the code delay: there are two components of the baseband signal, the in phase (I) and quadrant (Q). They both depend on the estimated carrier phase error, Doppler error and code delay error [156].
- The correlation output model: This model is used to extract the data from the GNSS baseband signal that is completely suppressed by the noise in the RF front end. For that reason, the GNSS receiver has to execute the correlation process between the dual local replicas and the incoming signal [155].

2.13.3. The GNSS signal acquisition

Signal acquisition is the process of determining the status of the incoming signal. This is to determine if it is possible for the GNSS receiver to process the received signal. This verification is carried out through the comparison of the received signal and local replicas. If the received signal and local replicas correlate properly, it means the incoming signal is healthy and the acquisition will be carried out accurately.

2.13.4. The GNSS signal tracking

The process by which the GNSS receiver attempts to generate a local duplicate of the incoming signal with similar parameters is referred to as signal tracking [157]. During the signal tracking, the carrier phase and the code delay are accurately estimated compared to the acquisition phase. The signal tracking requires less spectrum power. The signal tracking and acquisition are based on the correlation function and three feedback loops [158].

- The discriminator function: in this case, the correlator output models are utilized to provide the scalable values for tracking errors in terms of carrier phase and code delay.
- The loop filters are used to minimize the impact of the noise that may be missed through initial filtration.
- The Numerical Controlled Oscillator (NCO): This oscillator is used to generate the GNSS PRN codes that correspond to the incoming signal. The oscillator further transforms the discriminator outputs to form the frequency that facilitates the generation of the local duplicates [159].

2.14. Summary and conclusion

The receivers for positioning systems calculate their location using the several signals received from the satellite in the common view, since the receiver needs four or more satellites to compute an accurate location and further allow satellite tracking and detection. Chapter two has provided a comprehensive analysis of the GNSS architecture, frequency allocation, signal structure, and prospective receivers. Furthermore, in chapter two the signal processing in the GNSS receiver is provided that include, the correlation outputs in the digital processing, signal acquisition and tracking. The baseband signal modulation controls the characteristics of the signal and the shape of the GNSS correlation function. The GNSS is used to obtain the PVT solution; the computation of this solution is the derivative of the pseudorange obtained from the correlator output model. The GNSS went through some evolution with the introduction of the innovative GNSS signals, the Galileo, BeiDou, and GPS L5 signals. The GNSS application offers attractive services in rural areas and in locations with a clear view of the sky. The clear view of the sky is not the only factor to consider; the satellite coverage is an additional factor to look for. Indoor applications and urban areas with congested communication channels have been added to the list of GNSS applications. Hence, the GNSS signal multipath along the satellite path is largely experienced in urban areas and indoor applications. For indoor applications, the power losses depend on the material being used for the building or structure, as shown in Figure 1.3 of Chapter 1. Chapter three will unfold the concept of GNSS signal multipath and further discuss the multipath propagation and mitigating techniques.

CHAPTER THREE

The GNSS multipath propagation and mitigating techniques

In this chapter, the GNSS signal multipath and mitigating will be discussed into details. The goals of this thesis are to use the concept of combined signal detection to lessen the effects of multipath signals on GNSS receivers. As a result, this chapter provides a clear picture of multipath signal characteristics and goes on to develop the maximum likelihood estimation algorithm for estimating the multipath signal in the receiving channel.

3.1. Background

The GNSS has been found to be useful in a variety of applications that require a high level of performance. However, there are several causes of errors that degrade the positioning function of the GNSS network that are discussed in chapter two. This chapter emphasizes the aspect of multipath propagation. Many of the stated positioning errors are continuous in all GNSS receivers and are reduced using common differential methods. However, the differences in the geographical position between the reference receiver and the station, the multipath of the receiver's location, and the number and amplitude of the multipath make it difficult to reduce the multipath error using differential techniques.

The differential methodologies are not capable of eliminating the errors triggered by the signal multipath along the satellite path. Previous research has consistently demonstrated that signal multipath causes significant inaccuracies in the PVT solution for both static and mobile users. Therefore, multipath is the leading topic in the sphere of GNSS. This chapter broadly provides three main sections: multipath propagation, a comprehensive review of multipath mitigation, and the simulation of the GNSS multipath in different conditions.

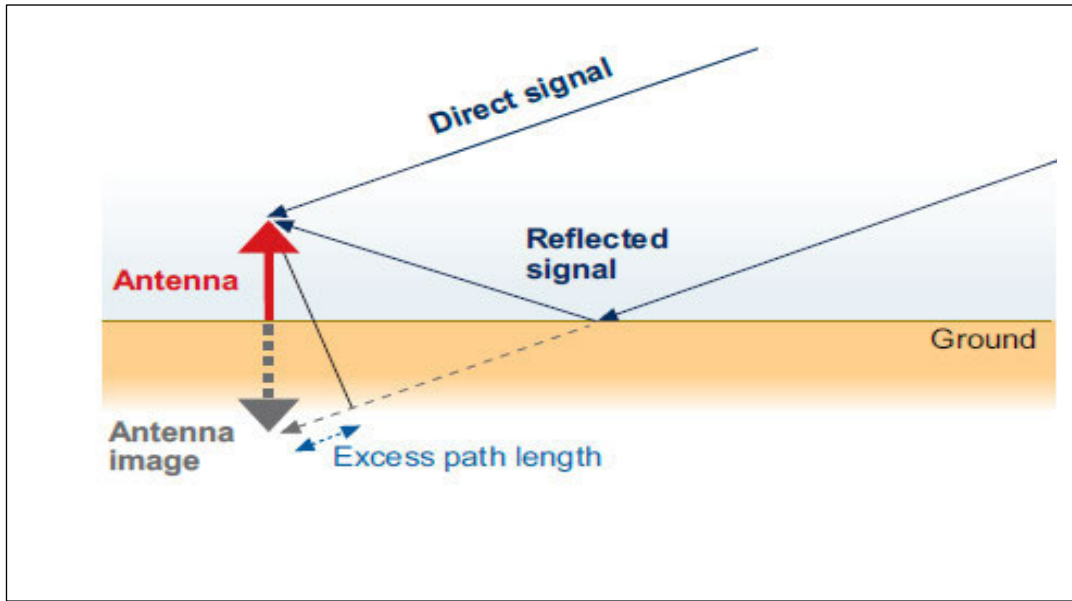


Figure 3.1: The Representation of the GNSS multipath [160].

The reflection of the GNSS signal from surfaces close to the receiver generally causes multipath propagation. In many cases, those surfaces are metal surfaces and buildings, and the reflection results in the formation of more secondary propagation paths as illustrated in Figure 3.1. The signals along the secondary path overlaid the desired direct signal path, and they have a long propagation period [161]. These signals have the ability to significantly distort the phase and amplitude of the signal along the direct path. Hence, this led to the deformation in the correlation functions. The error bias is introduced by the distorted correlation shape. In other environments, such as the severe multipath locations, the line of sight is completely obstructed, and the user will only receive the reflected signals. The phase measurements are very important, and such errors can reach up to a few meters, which is not good for a GNSS network in terms of its reliability. Furthermore, because multipath error is spatially decorrelated quickly, it cannot be removed using difference processing. There are many applications that are using high-performance receivers where the Frequency Locked Loop (FLL) is used to calculate the velocity approximations using the relationship of the following mathematical expression:

$$V_r = \lambda_t f_d \quad (3.1)$$

Where the V_r represents the radial velocity and the λ_t represents the transmitted wavelength. The final result of expression is called the delta – range measurements. In case the accumulation of the Numerical Controlled Oscillator (NCO) has been done and the velocity is entirely integrated, the results will be relative displacement considering the beginning of the velocity integration. Once the given integration interval is completed, the whole number of the Doppler cycle will be counted by then and the fraction of the Doppler cycle will remain. Equation (3.2) assume that the signal is synchronized in the frequency and as the results the Doppler shift of the received signal and the carrier frequency has been detached by the digital technique. Other applications are still using analog systems to remove the carrier frequency.

$$Y_0(t) = \delta_0 \sum_{n=-\infty}^{\infty} x(m) \sum_{p=0}^{M_c-1} 1 \sum_{q=0}^{N_c-1} c(k) \lambda_T(t - \tau_0) + w(t) \quad (3.2)$$

$$Y_0(t) = \delta_0 \sum_{n=-\infty}^{\infty} x(m) \lambda_T(t - \tau_0) + w(t) \quad (3.3)$$

where the:

- $\lambda_T(t)$ - represents the transmitted wavelength or the signal pulse filtered by LNA.
- $w(t)$ – is the thermal noise

The main purpose of the synchronization technique using Equation (3.2) is to develop an approximation of the time delay(τ_0) and phase carrier data entrenched to the amplitude of the phase complex.

3.2. Modeling of the propagation and transmitting channel

The data between communication devices is transmitted using channels. The communication channels compromise any service and media within the categories used to transfer the signal between the receiver and transmitter [162]. The GNSS network communicates with the aid of the following.

- The transmitting antenna
- The signal power propagation channel
- The receiving antenna (static or dynamic)

The signal propagation channels signify the process of emitting the GNSS signal using the satellite path from the satellite (the transmitter) to the receiver.

The chronological concept of the signal transmission from the transmitter (satellite) to the receiver using the antennas is depicted in Figure 3.2.

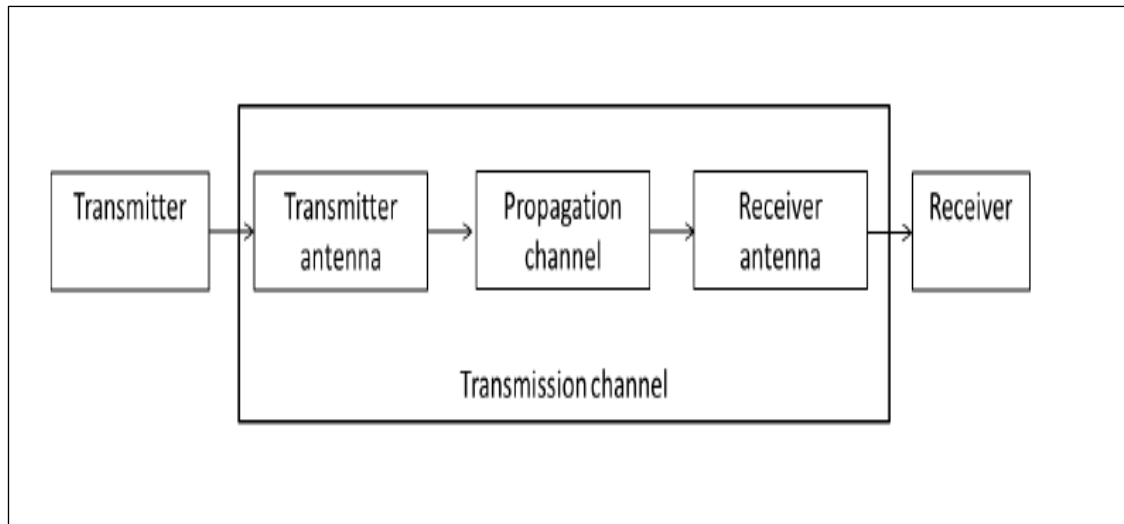


Figure 3.2: The combine propagation and transmitting channel.

The satellites have the transmitting antennas that transfer the signal to the GNSS receiver through the propagation channel.

3.2.1. The transmitter and receiver antenna

This is a satellite antenna that is designed to radiate the GNSS signal. The interfacing between the space segment and ground segment is anticipated to use two Right Hand Circular Polarization (RHCP) radio frequency links. Those links are L1 and L2, respectively. The receiver has the antenna with the ability to prompt two effects on the received GNSS signal, namely:

- The phase shift and group delay on the GNSS signal
- Introduce the polarity losses as the results of discrepancies experienced by the receiver in the incoming signal and influences the power of the received GNSS signal.

3.2.2. Multipath propagation channels

The transmission of the EM wave between the transmitter and the receiver is met with the following disruptions:

- Interference
- Multipath
- Atmospheric

The EM wave disruptions brought by the atmosphere are expected to occur in the troposphere and ionosphere respectively. The multipath is caused by the

scattering of the EM wave. Hence, the balance of chapter three will emphasis the modelling of the propagation channel if there is a multipath perturbation and the propagation channel parameters are predicted adhering to three forms of models [163].

- **Deterministic model** – that uses EM multipath for the prediction and further necessitate the narrative of the 3D to predict the multipath precisely.
- **Statistical model** - the parameters of the channels are estimated randomly using widespread of the statistical and experimental data.
- **Hybrid model** - this model is the combination of both statistical and deterministic models respectively.

3.3. The GNSS transfer function along the transmission channel

The multipath signal contains the code delay and the phase rotation. Therefore, the GNSS multipath signal can be used to model the direct incoming signal, and the transmitting channel is deemed to function as the linear filter of the GNSS receiver [164]. The impulse response of the GNSS signal along the transmitting path is also known as the Dirac delta function due to the presence of the multipath signal. Hence, characterizing the GNSS transfer channel is likely to instill timing concerns for both multipath and direct signals. This section provides a brief discussion of the received signal, the exact model, the wideband model, and the narrowband model using the GNSS transfer function for the transmission channel.

3.3.1. Received signal

The multipath signal has the serious impacts in the GNSS signal, especially those triggered by the user location. The multipath of the incoming signal in the GNSS receiver is calculated using the concept of DLL [165]. The DLL is used to estimate the code delay and the numerical expression of the GNSS signal power for the precise duration ($R_{\text{BPSK}}(\gamma) = \{1 - \frac{|\gamma|}{T_c}, |\gamma| \leq T_c\}$).

The impulse response of the GNSS of the wideband signal model is deemed to be capable of adding GPS L1 and GPS L5 of the incoming signal irrespective of the noise level as illustrated in equation (3.4).

$$S_T(t) = S_{T,DC,L1}(t) + S_{T,PC,L1}(t) + S_{T,DC,L5}(t) + S_{T,PC,L5}(t) \quad (3.4)$$

where the:

- The function of $S_{T,DC,L1}(t)$ and $S_{T,DC,L5}(t)$ denote the GNSS data module for GPS L1 and GPS L5, respectively.
- The $S_{T,PC,L1}(t)$ and $S_{T,PC,L5}(t)$ denote the GNSS pilot module for GPS L1 and GPS L5, respectively.

The GPS L1C, GPS L5, Galileo E1 and E5a contain dual channels for data and pilot. The architecture of the DLL in GNSS receivers are configured to use data module only, pilot module only and both data and pilot components [166].

3.3.2. Exact model

The exact channel model necessitates the calculation of the frequency response function of the channel in the whole spectrum for each and every GNSS signal. This is due to the absence of an accurate assumption of the mathematical expression of the transfer function [167]. The resultant transferring function of the exact model is similar to the wideband, as demonstrated in [168].

3.3.3. Wideband model

The transfer function of the wideband model is based on the assumed mathematical expression. The wideband assumes that the considered direct signal and reverberation are affected by the attenuation, code delay, and phase rotation generated within the system [169]. Hence, both the frequency and baseband impulse response relating to the wideband signal models along the transmission channel are given by

$$h_{FR}(t) = \sum_{M=0}^M \alpha_M \delta(t - \tau_M) e^{j2\pi f_{D,M} t + j\theta_M} \quad (3.5)$$

$$h_{BI}(t) = \sum_{M=0}^M \alpha_M e^{-(j2\pi F - f_{D,M} t)\tau_P + j\theta_M} \quad (3.6)$$

where the:

- P represent the multipath number
- α_M represents the amplitude of the baseband signal in case of multipath analysis. The A_0 represent the output signal at the receiving antenna that would have been delivered in case there is no multipath in the prospect.
- δ is denoting the Dirac distribution
- τ_p is representing the delaying code for the M^{th} multipath component of the antenna output of the end user or receiver.

- $f_{D,M}$ is representing the Doppler shift effect for the M^{th} multipath component of the antenna output of the end user or receiver.
- θ_M represent the phase shift M^{th} multipath component of the antenna output of the end user or receiver.

3.3.4. Narrowband model

The transferring function of the narrowband modeling is based on the mathematical expression assumption being made, and the transfer function is deemed to be constant over the bandwidth channel [170]. Hence, both the frequency and baseband impulse response of the narrowband signal transmission are given by the mathematical expression in equation (3.7).

These apply to all GNSS signal that are transformed to the baseband.

$$h_{FR} = \alpha \delta(t - \tau) e^{j\theta} \quad (3.7)$$

$$h_{BI} = \alpha e^{-j2\pi f \tau_e} e^{j\theta} \quad (3.8)$$

- α is used to represents the attenuation factor of the output signal at the receiving antenna
- τ is representing the delaying code of the signal in the output of the receiving antenna
- θ_1 represent the phase shift of the signal of the receiving antenna

The excess of the phase diversity and code delay for the multipath is ignored in the frequency and impulse response for all narrowband transmission; hence the narrowband model will not differentiate between the direct signal and their echo signal.

3.4. Multipath parameters definition and computation

There are four crucial parameters characterized multipath parameters in the output of the antenna and those parameters are $(\alpha_p, \tau_p, f_{D,p}$ and $\theta_p)$, the simulated features of α_p and θ_p are reliant to the design considerations of the GNSS antenna and the signal broadcasting channel.

Therefore, the parameters mentioned are calculated using the following numerical methodologies. The calculation and estimation of the signal amplitude for GPS L1 frequency band

$$\alpha_{p,L1} = \frac{E_{L1}(e_{r,p}) \cdot I_{L1}(e_{r,p})}{V_o} \quad (3.9)$$

The calculation and estimation of the signal amplitude for GPS L5 frequency band

$$\alpha_{p,L5} = \frac{E_{L5}(e_{r,p}) \cdot I_{L5}(e_{r,p})}{V_o} \quad (3.10)$$

The calculation and estimation of the signal phase shift for GPS L1 frequency band

$$\theta_{p,L1} = E_{L1}(e_{r,p}) \cdot L_{L1}(e_{r,p}) \quad (3.11)$$

The Calculation and estimation of the signal phase shift for GPS L5 frequency band

$$\theta_{p,L5} = E_{L5}(e_{r,p}) \cdot L_{L5}(e_{r,p}) \quad (3.12)$$

where the:

- $e_{r,p}$ is the direction of arrival of the replica signal.
- $E_{L1}(e_{r,p})$ and the $E_{L5}(e_{r,p})$ are the electric field elements of GPS L1 and GPS L5.
- $L_{L1}(e_{r,p})$ and the $L_{L5}(e_{r,p})$ are the effectiveness of the GNSS user antenna for GPS L1 and GPS L5
- V_o is the open circuit voltage acquired to embrace the ideal arrangement of the antenna configuration.

The Doppler shift $f_{D,P}$ effect and the code delay τ_p are used to influence the characteristics of the satellite dissemination channels. In case of the 3D scenarios and mobile space satellites, the effect of the Doppler shift for GPS L1 and GPS L5 are given in equation (3.13) and (3.14).

The effect of the Doppler shift for GPS L1

$$f_{D,P,L1} = \frac{f_{L1}}{c} \cdot v_{r,k} \quad (3.13)$$

The effect of the Doppler shift for GPS L5

$$f_{D,P,L5} = \frac{f_{L5}}{C} \cdot v_{r,k} \quad (3.14)$$

where the:

- C is representing the speed of light in the vacuum
- v is the vectorial speed of the GNSS receiver and the
- $v_{r,k}$ is equal to $v \cdot e_{r,p}$, therefore this term represents the effectiveness of the receiver vector speed.

Numerous software tools have been developed to simulate and analyze the impact of the multipath signal for land, maritime, and aeronautical applications that require the configuration of the navigation parameters to be in 3D format. Section 2.8 of Chapter 2 provides the basic architecture and a brief discussion of the GNSS hybrid Galileo/GPS receiver. Hence, this section is envisioned to provide a comprehensive discussion of the GNSS output at the receiving antenna. This discussion includes the typical signal expressions that are anticipated in the presence of multipath conditions [53]. The input signals of the GNSS receiver are processed by the Radio – Frequency (RF) and the Intermediate Frequency (IF) signal-processing block where the code and phase delay are provided. The innovative block diagram of all crucial stages that are involved with the processing of the GNSS signal at the receiving antenna is provided in Figure 3.3.

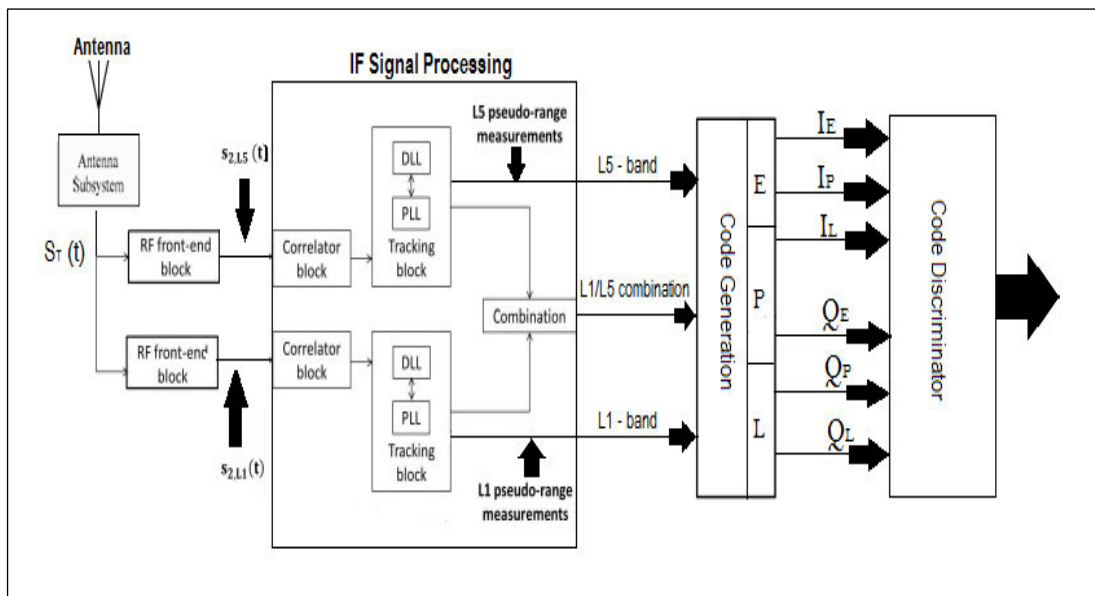


Figure 3.3: Advanced architecture of GNSS receiver.

This is a comprehensive architecture of the GNSS receiver to provide more details than the one used in Figure 2.6. The first block in the diagram in Figure 3.3 represents the antenna subsystem, and a brief description is provided. For the sake of clarity, the expression of the GNSS receiver signal is represented in equation (3.14), with the noise term omitted, and these signals are deemed to be amplified, down converted, sampled, and quantitated on both L1 and L5, respectively. The total signal splits to form two new signals with respect to the sampling time denoted by t for L1 and L5, as expressed below. The RF signal for L1 frequency band

$$S_i = \sum_{p=1}^P \alpha_{p,i} C_{p,i} (t - \tau_{d,i}) \cos(360^\circ (f_{IF,i} + f_{D,P,i})t_i + \theta_i) \quad (3.15)$$

where the: $i = 1, 5$

- $\alpha_{p,L1}$ and $\alpha_{p,L5}$ are the amplitude for L1 and L5, respectively.
- $C_{d,L1}$ and $C_{d,L5}$ are the data waveform for GPS L1 and GPS L5.
- $\tau_{d,L1}$ and $\tau_{d,L5}$ represent the code delay for GPS L1 and GPS L5.
- $f_{L1,IF}$ and $f_{L5,IF}$ denote the intermediate frequency for both frequency bands L1 and L5.
- θ_{L1} is the carrier phase for GPS L1
- θ_{L5} is the carrier phase for GPS L5

3.4.1. Acquisition block

The IF section contains the acquisition block that is used to further process the signal following the notation given by the RF front end block. The acquisition block is also called the correlator block; hence, it is used to detect the existence of the GNSS signal and further provide the approximation of the propagation time relevant to the previously detected signal [157]. The signal through the acquisition block is deemed to not be separated into I and Q samples as yet and is expressed as follows:

$$S_{IF} = A_p \cdot D_{nav} \cdot (t_{IF} - \tau_{IF}) \cdot \delta_R \cdot \cos [360^\circ (f_{IF} + f_{DS}) \cdot t_{IF} + \theta_{Offset}] \quad (3.16)$$

where the:

- A_p is the amplitude of the baseband signal after reaching the acquisition block
- τ_{IF} is the code delay in the acquisition block

- δ_R carrier phase in the acquisition block that is influenced by the intermediate frequency.
- f_{DS} is the frequency ratio across the phase and quadrant samples.
- D_{nav} represents the navigation data message after the correlation blocks detected the presence of the GNSS data
- t_{IF} denotes the actual time between two sequential navigation data samples throughout the sampling time. This is the mathematical expression that is being integrated in the system with the relevant sampling equations to provide the estimation of the propagation time
- θ_{Offset} this is the carrier phase offset

Equation (3.15) provides the necessary evidence that the acquisition of the navigation data signal is the global search for the precise standards of the Doppler frequency and propagation time, respectively. However, their possibilities of cold start correlation where the acquisition block of the receiver have to perform a profound exploration of the entire GNSS signal coding from the antenna to the correlator block itself without the preceding information from the RF end band. The cold start is anticipated to result in a substantial time delay due to the implementation of the actual acquisition process. Therefore, the acquisition time depends upon the following parameters: acquisition algorithm, Doppler frequencies, and the number of channels available, the correlation per channel, code length and the condition of the signal.

3.4.2. Tracking blocks

The signal Doppler frequency and the code delay are refined and estimated in the tracking blocks. The tracking block is also used for the approximation of the carrier phase and further provides the continuous update approximation for signal conditions [170]. There are two distinct sets of locks that are looped, the Delay Lock Loop (DLL) and the Phase Lock Loop (PLL), respectively. The DLL is used to provide an accurate estimation of the code delay and its changes as time proceeds; the PLL is used to provide an accurate approximation for both carrier phase and Doppler frequency and the expected rate of change as time proceeds. The data signal is then divided into two streams, I and Q, respectively, where the codes are generated and mixed with early E, late L, and prompt P as illustrated in Figure 3.3.

The tracking loop is continuously and constantly updated so that it can match the phase of the received data signal, and the signal correlation values are molded [171]. The signal correlation values are modeled adhering to the notation of equations (3.14) and (3.15). Hence, at the sampling time t and the delay, E , L , and P are assumed to be the only data and expressed as follows: The estimation of the local code replica for E

$$C_{D,E}(t) = C_D \left(t - \delta + \frac{\Delta}{2} \right) \quad (3.17)$$

The estimation of the local code replica for L

$$C_{D,L}(t) = C_D \left(t - \delta - \frac{\Delta}{2} \right) \quad (3.18)$$

The estimation of the local code replica for P

$$C_{D,P}(t) = C_D (t - \delta) \quad (3.19)$$

The error of the signal after passing through the loop filter is computed by the discriminator, and the pure functional mechanism used to maintain frequency locks is designed to recover the navigational data during the tracking process whenever it is required. The carrier aiding process is when the measured carrier loop is fed back to the coding loop. Carrier-AID is also involved with the improvement of code tracking by reducing the large influence of the data signal dynamics [172]. The purpose of the DLL discriminator is to extract the code delay error, which is processed by the correlator outputs depending on the combination of E , L , and P samples. Therefore, the correlator's output samples are used to establish the code, frequency, and phase code, categorized as follows: early minus late envelope, dot product power, and coherent.

- Early minus late power

$$DLL_{out} = (I_E^2 + Q_E^2) - (I_L^2 + Q_L^2) \quad (3.20)$$

This equation represents the non-coherent value of DLL, suggesting that the DLL is capable to operate autonomously of the data demodulation and residual phase carrier. The DLL output is deemed to be completely locked if the condition in equation is met.

$$DLL_{out} = 0 \text{ and the } (I_E^2 + Q_E^2) = (I_L^2 + Q_L^2) \quad (3.21)$$

- The early minus late envelope

$$DLL_{out} = \frac{\sqrt{(I_E^2 + Q_E^2)} - \sqrt{(I_L^2 + Q_L^2)}}{\sqrt{(I_E^2 + Q_E^2)} + \sqrt{(I_L^2 + Q_L^2)}} \quad (3.22)$$

This is the normalized version where the division is being applied to remove the sensitivity of the amplitude and this is extensively adopted for GNSS GPS receivers.

- The coherent

The architecture of the coherent includes the use of the term (I_P) that used to remove the data that is deemed to be unnecessary along the processing. The complete expression is:

$$D_{coherent}(\gamma) = (I_E - I_L)\cos(\delta) + [(Q_E - Q_L)\sin(\delta)] \text{sign}(I_P) \quad (3.23)$$

The estimate of data δ is removed using the definite carrier path to achieve the better performances compared to non – coherent model.

- The dot power product

The dot product is used for lower computational cases and this architecture uses six values of the correlator where the prompt value is used to multiply each term as shown in equation (3.25).

$$D_{dot\ power}(\gamma) = (I_E - I_L)I_P + (Q_E - Q_L)Q_P \quad (3.24)$$

Numerous GPS correlators in the markets uses the replicas of the early minus to ease the computation of the dot power.

3.5. The Influence of the multipath signal on the GNSS code and pseudorange

The primary goal of this section is to provide an assessment of the multipath influence on code delay approximation and pseudorange measurement, respectively [173]. The historical and current activities in the field of GPS innovation are carried out with the determination to improve the navigational signal compared to the legacy GPS systems, with the most promising approach of presenting the signal in a combination of different views being considered.

3.5.1. The definition of the raw code and range error for multipath signals

The delay codes of the DLL approximation are converted to pseudorange measurement codes as soon as they reach the receiver. The outputs of the DLL are the code delay and are transformed into pseudorange measurement

format. Hence, these innovative pseudorange measurements are called the raw multipath range error and are numerically expressed in equation (3.25).

$$M\varepsilon_{L1C} = C_{data} \cdot \varepsilon_{tracking} \quad (3.25)$$

where the:

- $M\varepsilon_{L1C}$ signify the multipath error of the GPS L1C signal
- C_{data} is the data waveform and the
- $\varepsilon_{tracking}$ is the code tracking error of the multipath signal

The range error for multipath raw code is categorized in three forms to express the involvement of the satellite constellations.

- The GPS L1 code pseudo-range measurements have multipath error and are represented by GPSL1C in equation (3.28) and by Galileo E1 in equation (3.29).
- The GPS L5 code produces pseudo-range measurements with multipath error and is represented by GPSL5 in equation (3.30) and by Galileo E5a in equation (3.31).
- The ionosphere-free GPS L5 + GPS L5 code pseudo-range measurements have multipath error, which is represented by in equation (3.28) for GPS L1C and GPS L5, and in equation (3.30) for GalileoE1 and GalileoE5a.

The GPS and Galileo have different ionosphere mediums to allow the transfer of the different signal modules and frequencies at different speeds. The GNSS receivers are well designed to measure the pseudorange from the space satellite using dual frequencies. Such measurements can be combined to form the ion-free pseudo-range measurements that are considered to be unaffected by the ionosphere delay of the first order. The first-order residual of the raw code ionosphere ranging error is defined using and for both GPS L1 and GPS L5 frequency bands, respectively. The following numerical expression is established to define the range error and the raw code for the ionosphere. From equation 3.43, the f_{L1} and f_{L5} signify the frequency links for GPS L1 and GPS L5.

$$\varepsilon_{rc \text{ Iono},L5} (f_{L5})^2 = \varepsilon_{rc \text{ Iono},L1} (f_{L1})^2 \quad (3.26)$$

Therefore, the GPSL1C/A, GPSL5, GalileoE1 and the GalileoE5a pseudo – code measurements are given by the following equations.

The GPSL1C/A - GPSL5

$$\beta_{L1C-L5} = f_a \beta_{L1C} + f_b \beta_{L5} \quad (3.27)$$

GalileoE1- GalileoE5a

$$\beta_{E1-E5a} = f_a \beta_{E1} + f_b \beta_{E5a} \quad (3.28)$$

- β_{L1C-L5} and the β_{E1-E5a} are denoting the pseudo –range code for GPS L1 C/A and the GPSL5, and the GalileoE1 and GalileoE5a respectively.
- $f_a = \frac{f_{L1}^2}{f_{L1}^2 - f_{L5}^2}$, where f_a is the regulating function to control the frequency moving from GPS L1 to GPS L5.
- $f_b = \frac{f_{L5}^2}{f_{L5}^2 - f_{L1}^2}$, where f_b is the regulating function to control the frequency moving from GPS L5 to GPS L1.

The following equations (3.31) and (3.32) represent the iono free L5 + L5 code pseudo – range measurements multipath error.

$$M\varepsilon_{L1C-L5} = f_a M\varepsilon_{L1C} + f_b M\varepsilon_{L5} \quad (3.29)$$

$$M\varepsilon_{E1-E5a} = f_a M\varepsilon_{E1} + f_b M\varepsilon_{E5a} \quad (3.30)$$

3.5.2. Evaluating the estimate of the code delay in the presence of multipath signal

For simplicity, the code delay needs to be estimated in a multipath free scenario to ensure that, the impact and the presence of the multipath signal will be accurately evaluated. The stability represented by

$$AC_{data} \left(\tau_{data} + \frac{\Delta}{2} \right) = AC_{data} \left(\tau_{data} - \frac{\Delta}{2} \right) \quad (3.31)$$

where the:

- $AC_{data}(\cdot)$ is the auto-correlation function of the data module of the received signal and point of constancy is reached if $\tau_{data} = 0$.

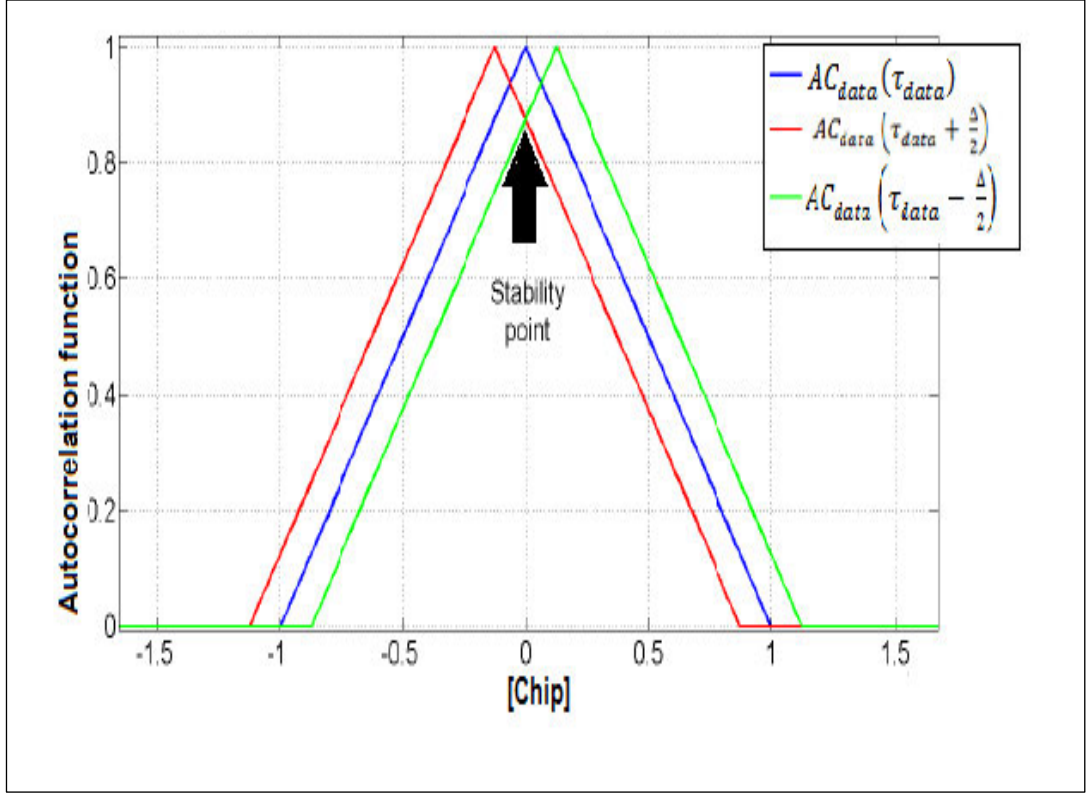


Figure 3.4: The Standardized correlator outputs for GPSL5 – without signal multipath.

Figure 3.4 show the evolution of three functional graphs: $AC_{data}(\tau_{data})$, $AC_{data}(\tau_{data} + \frac{\Delta}{2})$ and, $AC_{data}(\tau_{data} - \frac{\Delta}{2})$ and the stability point where the chips Δ is between $[-1.5; 1.5]$ for GPSL5-P. This concludes the insignificant error in the estimation of the delay code. The second step in evaluating and comprehending the impact of the multipath code delay is to consider the situation where the original direct signal and the resonance or echo are received by the receiving antenna at the receiving end. The amplitude a_0 and the change in chip $\Delta\delta_1$ are being incorporated to the equation (3.34) and (3.35). The stability of the code delay in the presence of the multipath signal is presented in the following way:

$$ST_{CD} = a_0 AC_{data}(\tau_{data} - \frac{\Delta}{2}) + a_1 AC_{data}(\tau_{data} + \Delta\delta_1 - \frac{\Delta}{2}) \quad (3.32)$$

$$ST_{CD} = a_0 AC_{data}(\tau_{data} + \frac{\Delta}{2}) + a_1 AC_{data}(\tau_{data} + \Delta\delta_1 + \frac{\Delta}{2}) \quad (3.33)$$

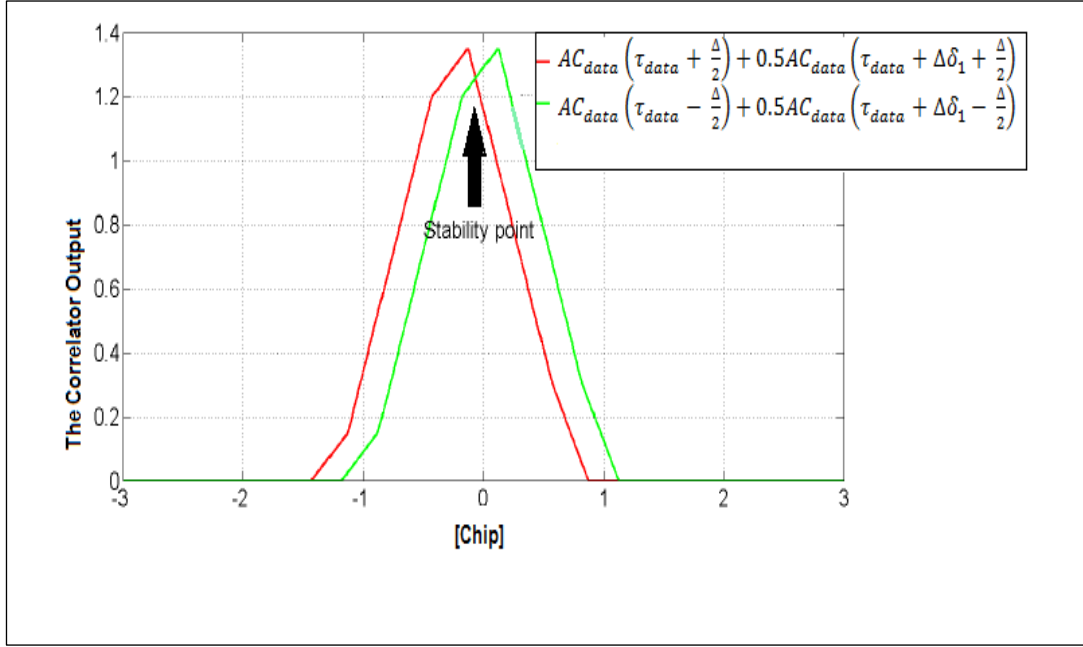


Figure 3.5: The standardized correlator outputs for GPS L5 – with the single echo signal.

Figure 3.5 shows the evolution of two functional graphs: $a_0AC_{data}\left(\tau_{data} + \frac{\Delta}{2}\right) + a_1AC_{data}\left(\tau_{data} + \Delta\delta_1 + \frac{\Delta}{2}\right)$ and the $a_0AC_{data}\left(\tau_{data} - \frac{\Delta}{2}\right) + a_1AC_{data}\left(\tau_{data} + \Delta\delta_1 - \frac{\Delta}{2}\right)$ in respect of the GPS L5-P function. The following assumptions were made: $a_0 = 0$, $a_0 = 0.5$ and the change in chip $\Delta\delta_1$ is $[-3; 3]$. Furthermore, Figure 3.11 shows that in the presence of the multipath, the correlator outputs GPS L5-P are pretentious due to the distortion that is entirely dependent upon the values of the amplitude, carrier phase resonance, and code delay. The stability point in this case is reached when the discriminator output is insignificant.

3.6. The analysis of the GNSS multipath performance for both Galileo and GPS

There are numerous activities in the field of space engineering to improve the overall navigation performance by integrating traditional and recent applications. Recently, we have witnessed the development of the European satellite Galileo and the Chinese satellite BeiDou, or compass. This is a very promising approach in the field of GNSS that optimizes the currently used modulation schemes.

The development of the Galileo and BeiDou has provided a significant improvement in terms of the navigation data code noise, the tracking strength in the narrow and wide bands, and the multipath. Hence, it is anticipated that the novel civil signal will be made available to the restructured GPS and Galileo satellites in the future, and errors such as the ionosphere error are expected to become less significant [174]. The ionosphere will be minimized through the computation of the ionosphere correction adhering to the dual frequency band and the use of the SBAS. Despite all of these efforts to improve GNSS performance, multipath and mitigation techniques continue to be a source of concern for navigation applications.

As a result, the impact of multipath is considered in many GNSS developments, as are techniques to mitigate such an impact. However, there are other concerns such as noise in the signal and signal distortion that are being considered in the design of Galileo and the innovative GPS. The most popular methodology to describe the impact of the multipath in the spectrum is to compute the multipath envelopes [175]. The multipath envelopes consider two options: one multipath signal and more than one multipath signal. The computation of the multipath error envelopes is not the only computing model available; there are more compound models available in the event that more than one multipath signal is present. The most popular models are the statistical channel models that are operated based on the parameters obtained from diverse environments[176]. Hence, the resultant multipath error will be computed for the GPS C/A and the Galileo signal.

3.7. The GNSS signal modulation and processing

There are three signal samples that are used to visualize the different criteria of the multipath [177]. The currently used GPS C/A represented by the BPSK (1) signal sample, CBCS (20%) and the BOC (1, 1). Figure 3.12 illustrates the autocorrelation of these signal samples.

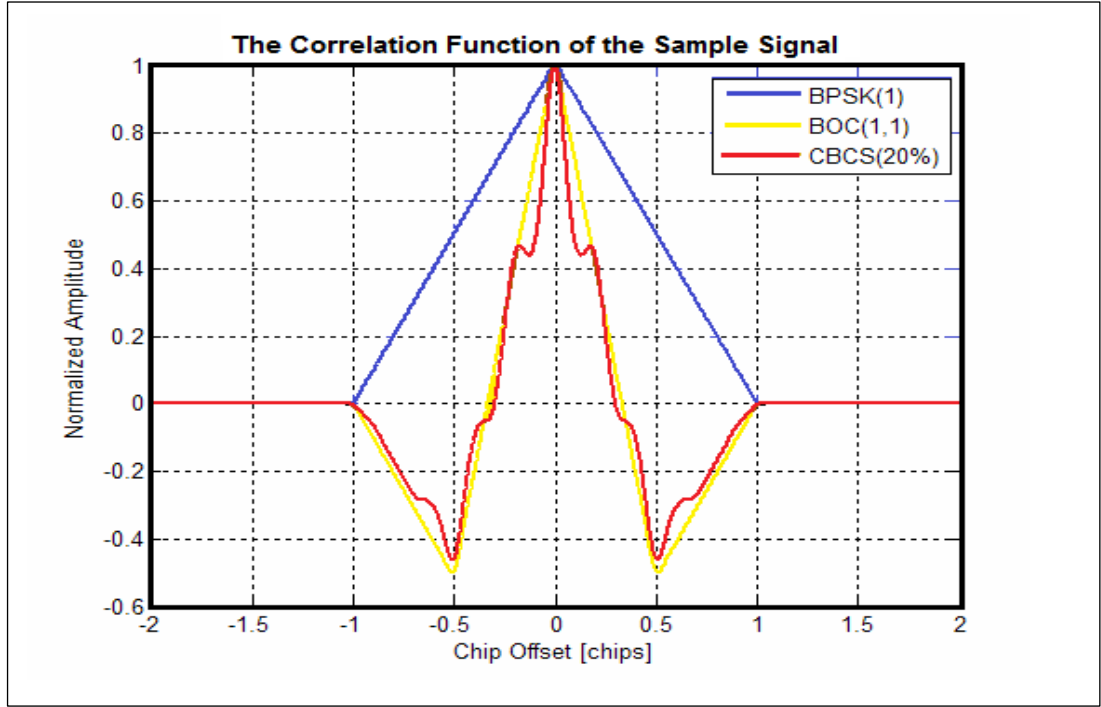


Figure 3.6: The analysis of the autocorrelation function between the three sample signals [177].

The BOC modulation uses the signal that is generated by the product of two signal signals in the baseband. These signals are non-filtered square signal with the sub – carrier frequency $f_{s,c}$ that is equal or higher than the chip rate r_c and the non – filtered PRN code with the chip rate value of $[\pm 1]$. Hence, the general equation to express the BOC modulation of the sine-phased signal with respect to t is:

$$Y_{BOC}(t) = \sum_k c_k h(t - kT_c) \sin(2\pi f_{s,c} t) \quad (3.34)$$

where the:

- c_k is representing the waveform sequence
- $h(t)$ is representing the Non-Return to Zero of the materialization code duration T_c

Equation (3.37) is the alternative model to define the BOC modulation is defined by the waveform chip.

$$Y_{\text{BOC}}(t) = \sum_k c_k \beta T_c(t - kT_c) \sin(2\pi f_{s,c}t) \quad (3.35)$$

The purpose of the square carrier in the BOC modulated signal is to divide the main section of the PRN spectrum into dual lobes carrier frequency. The BOC modulation parameters are denoted by BOC $(f_{s,c}, r_c)$ for the GPS and BOC (n, m) for Galileo signal.

3.7.1. Weighted multipath error envelopes

There are two schemes for the multipath error envelopes that function differently. The multipath is scaled by the scheme one error envelope based on its amplitude and distribution path. The distribution of the direct path amplitude adheres to the Rayleigh distribution, especially in the signal-shadowing scene [178]. The multipath error envelopes differentiate the model between the near reflection, direct path, and far reflection. Hence, the distribution of the near multipath signal reflection subjected to the delay τ is represented in the equation.

$$P_{\text{NMS}}(\tau) = \frac{1}{\tau_0} e^{-\frac{\tau}{\tau_0}} \quad (3.36)$$

With this equation it is assumed that $P_{\text{NMS}}(\tau) = P_{\text{MD}}(\tau)$. This multipath power is linked to the $P_{\text{AD}}(\tau)$ is the amplitude distribution. Hence, the new equations will be

$$P_{\text{MD}}(\tau) = \frac{1}{\tau_0} e^{-\frac{\tau}{\tau_0}} \text{ and } P_{\text{AD}}(\tau) = \frac{C_r}{\sqrt{\tau_p}} e^{-\frac{\tau}{\tau_p}} \quad (3.37)$$

The modelling of the multipath delay uses $P_{\text{MD}}(\tau)$ and the $P_{\text{AD}}(\tau)$ for the multipath amplitude modelling, the C_r reflection coefficient and the τ_p for the path delay. This is very similar to the statistical channel mode. This model suggests the following:

- The long delayed multipath is likely to occur more regularly than short delayed multipath.
- The comparatively weak multipath signal path is caused by the long geometrical path delay.

Adhering to equation (3.38), the combined multipath distribution $D_C(\tau)$ amplitude and delay is:

$$D_{C1}(\tau) = P_{MD}(\tau)P_{AD}(\tau) \frac{C_r}{\tau_p\sqrt{\tau_p}} e^{\frac{3\tau}{2\tau_p}} \quad (3.38)$$

Equation (3.38) is then used to scale the envelope of the multipath error and the coefficient reflection is involved with the computation of the multipath error.

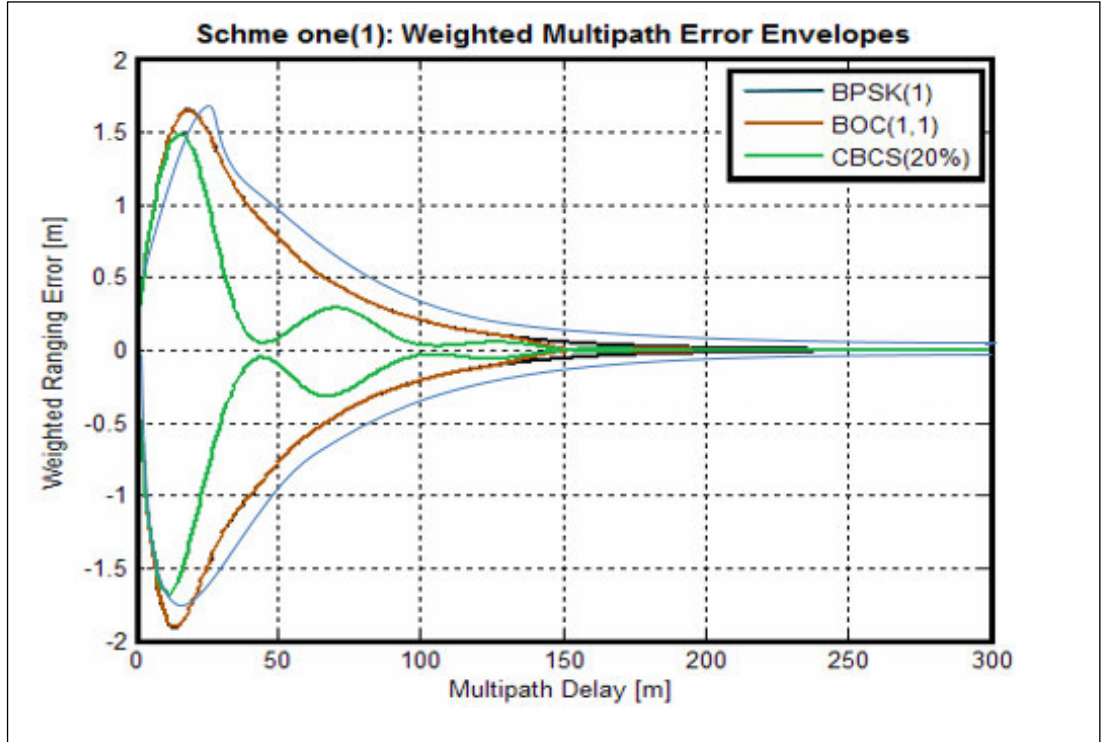


Figure 3.7: The Evaluation of weighted multipath error envelopes between the three GNSS sample signals.

Figure 3.7 shows that there is no substantial variance between the BOC (1, 1) and BPSK (1) modulated signal samples. The performance of the CBC is much better than the other two signal samples. Hence, the CBC-modulated signal sample is the short-delay multipath. The envelope error multipath analysis always represents the worst-case scenario, similar to the power delay method and the profile statistical channel model [179]. The second scheme of the weighted multipath error envelope adheres to both scheme one and the power delay profile of multipath error. Other than using comprehensive statistical data, it assumes a simple power delay profile.

The distribution equation with the relative amplitude α_r is expressed as:

$$D_{C2}(\tau) = \frac{\alpha_r}{\tau_0} e^{\frac{-\tau}{\tau_0}} \quad (3.39)$$

Equation (3.41) presents the equitably qualitative performance evaluation of multipath error by computing the area enclosed by the envelopes.

3.7.2. The predictable multipath errors code

The data in Table 3-1 is expanded to provide insight into the detail signal parameters considered for Galileo signals and the innovative GPS L5 signal using the concept of weighted multipath error envelopes [180]. Table 3-1 provides the multipath signal computing parameters for L1-L5 and the E5-E6 frequency bands. The navigation data messages must protected with three error encoding levels to improve the fame and bit error rate.

- The Cyclic Redundancy Check (CRC) detects transmission errors by including a supplementary checksum bit in each frame [181].
- The half-Forward Error Correction (FEC) is used to encode the receive signal using the convolutional code by inserting one additional data bit per message [182].
- The interleaving block helps avoid the burst errors, ease the work done by the FEC, and avoid the dispersal of the error along the entire data frame.

The Galileo has four types of data that are enabled to be carried by different radio navigation signals, and they provide a clear relationship between the frequency links L1-E5-E6.

- The Safety of Service (SoL) signal data denoted by the: $D_{L1}(t)$ and $D_{E5}(t)$
- The Public Regulated Service (PRS) signal data represented with the following terms: $D_{L1}(t)$ and $D_{E6}(t)$
- The Commercial Service (CS) signal data: $D_{E5}(t)$, $D_{L1}(t)$ and $D_{E6}(t)$
- The Open Service (OS) signal data mostly available to all users: $D_{L1}(t)$ and $D_{E6}(t)$

Table 3-1: The parameters for GPS and Galileo constellation

Signal Parameters	L1 Link			
Frequency Band	E2-L1-E2 (PRS)	E2-L1-E2 (OS)	E2-L1-E2 (OS)	L1(GPS)
Carrier wavelength [m]	0.190	0.190	0.190	0.190
The Modulating scheme	$BOC_{cos1}(15,2.5)$	MBOC(5.1.1/11)	BOC(1.1)	BPSK(1)
The Chip Length [m]	117.22	293.05	293.05	293.05
Central Frequency [MHz]	1575.42	1575.42	1575.42	1575.42
The Chip Rate [Mcps]	2.56	1.023	1.023	1.023
The Bandwidth [MHz]	40	24	24	24
Signal Parameters	E6 Link		E5 – L5 links	
Frequency Band	E6(CS)	E6(PRS)	GPSL5	E5ab(OS)
Carrier wavelength [m]	0.234	0.234	0.255	0.252
The Modulating scheme	BPSK(5)	$BOC_{cos}(10.5)$	BPSK(10)	AltBOC(15.10)
The Chip Length [m]	58.61	58.61	29.31	29.31
Central Frequency [MHz]	1278.75	1278.75	1176.45	1191.80
The Chip Rate [Mcps]	2.56	2.56	10.23	10.23
The Bandwidth [MHz]	24	40	22	51 ²

The initial base line of the Galileo and L1 OS signal introductions involved the replacement of the BOC (1.1) with the MBOC modulation.

The MBOC is also expected to improve the GPS L1C signal. The use of the AltBOC (15.10) modulation improves performance in terms of mitigating multipath using a wider bandwidth. The wider bandwidth has the constant envelope to offer improved efficiency.

3.8. The GNSS signal multipath detection and monitoring

This section provides a comprehensive review of the numerous approaches that are used to monitor the multipath effect. This is very important since it helps improve the signal quality in case signal interference or multipath are detected. The discussion of these approaches is articulated in respect of their realistic and meaningful benefits and downsides, including the possibility of instant multipath detection.

3.8.1. SNR monitoring

The SNR multipath monitoring algorithm can be implemented in two approaches. The first approach is based on the theoretical computation of the data obtained from the link budget. The second approach to SNR monitoring is based on the polynomial definition of the anticipated C/N_0 adhering to the elevation angle obtained from the calibrating measurements [183].

3.8.2. The C/N_0 profiles recordings

This monitoring algorithm needs the C/N_0 remark recorded by each and every satellite in the view. The mathematical expression of the obtained C/N_0 profile is expressed in terms of elevation angle E and the coefficient a_n of the p^{th} polynomial order [184]. In many cases the antenna is assumed as the second polynomial order.

$$C/N_0 = \sum_{n=0}^p \alpha_n (A, E) \quad (3.40)$$

In case the antenna pattern rotation is not symmetrical to the vertical line, the function will result to the elevation E and azimuth A as shown in equation (3.40).

3.8.3. The link based budget computations

In this case, the receiver uses the C/N_0 obtained information to compute the link budget, the general expression is defined in equation (3.40) and adheres to the received power P_r and the density of the spectrum noise N_s . Equation (3.41) also has the satellite transmitted power P_T for the specific signal, the gain for the transmitting antenna G_T and gain pattern for the receiving antenna G_R , atmospheric losses L_A , the satellite between the receiver and the satellite R , the carrier wavelength λ and the spectrum losses N_0 .

$$C/N_0 = \frac{P_r}{N_s} = \frac{P_T G_R G_T}{4\pi R^2 L_A} \cdot \frac{\lambda^2}{4\pi} \cdot \frac{1}{N_0} \quad (3.41)$$

The main shortcoming of this approach is the difficulties that are frequently encountered during practical involvement to obtain the required information. The parameters must be known accurately, especially the gain pattern for the transmitter and the receiver [185]. The circuit of the receiving hardware is responsible for the regulation and control of the spectral noise density. The noise parameters may not be available or known in some cases, and the polarization losses are the additional parameters that are likely to affect the computation.

3.8.4. Monitor thresholds

According to [186] the threshold monitoring is using the theoretical standard deviation to compute the predictable C/N_0 values and expressed as following:

$$Q_{C/N_0}^2 = \frac{1}{M T^2} (1 + 2TC/N_0) \quad (3.42)$$

Where the:

- T is representing the coherent integrating time
- M denote the total number of the integration to achieve the required estimation of C/N_0

The integration time settings of the GNSS receiver is $T = 0.02$ seconds adhering to 50Hz of the data rate.

3.8.5. Code Minus Carrier (CMC) monitoring

The CMC multipath monitoring is using the algorithm of differencing the carrier and code observations since both observations are likely to be affected by the presence of the multipath signal. Because the carrier multipath is much smaller than the code multipath, it is normally hidden in CMC monitoring analysis [187]. Hence, the CMC is appropriate for code multipath monitoring. The carrier and code observations are expressed as follows:

The code observes an equation.

$$P_{\text{code}} = D_{\text{S\&R}} + \beta(dt_s - dT_r) + d_I + d_T + \tau_{\text{PR}} \quad (3.43)$$

The code observing equation

$$P_{\text{carrier}} = D_{\text{S\&R}} + \beta(dt_s - dT_r) - d_I + d_T + \lambda N_a \tau_\delta \quad (3.44)$$

where the:

- $D_{\text{S\&R}}$ signifies the geometric range between the satellite and the receiver
- dt_s presents the error in the satellite clock
- dT_r denotes the error in the receiver clock
- d_I and d_T are representing the Ionospheric path delay and the Tropospheric delay respectively.
- λ is the carrier path wavelength
- N_a represent the integer phase ambiguity
- τ_{PR} and τ_δ represent the sources of error and noise, the carrier or code noise and carrier or code multipath

The formation of the CMC has numerous advantages, such as the elimination of the tropospheric path delay, ephemeris error, and clock errors. According to [68], in order to detect the presence and influence of the multipath consistently, the trend of the long periodic ionosphere must be eliminated, as must the effect of the thermal noise. Such interventions require the digital band pass filter to be applied in the data monitoring and are called filtering of the CMC observations, as illustrated in Figures 3.14 and 3.15.

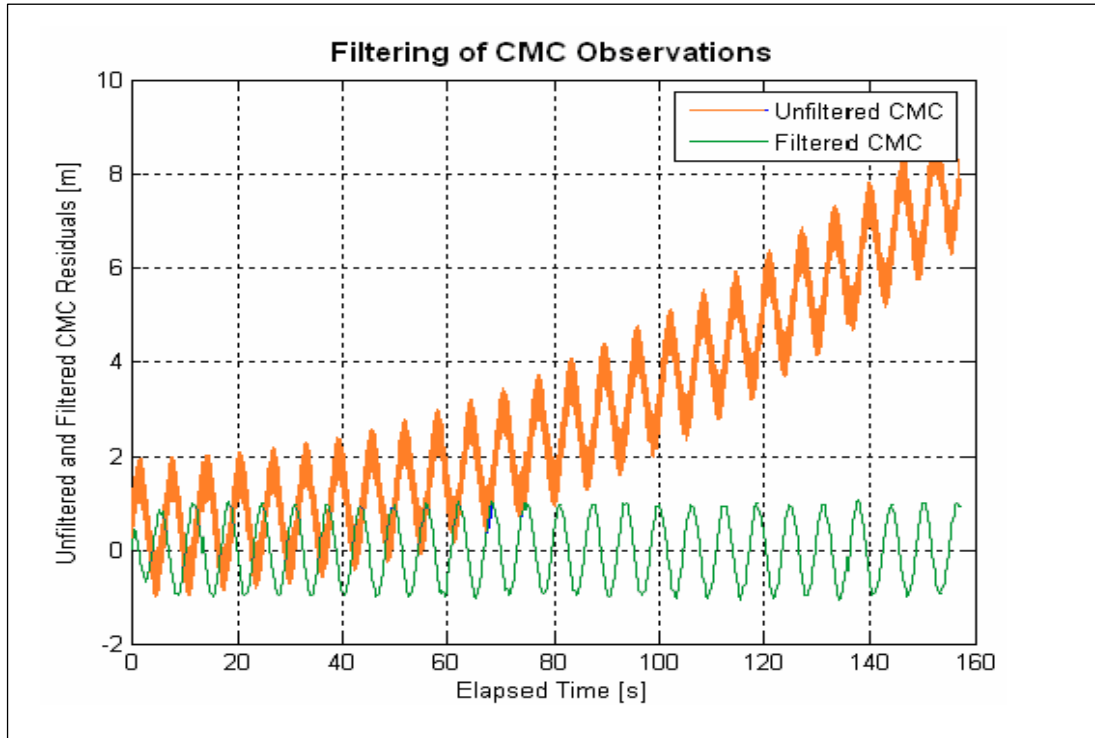


Figure 3.8: The filtration of the simulated CMC observation.

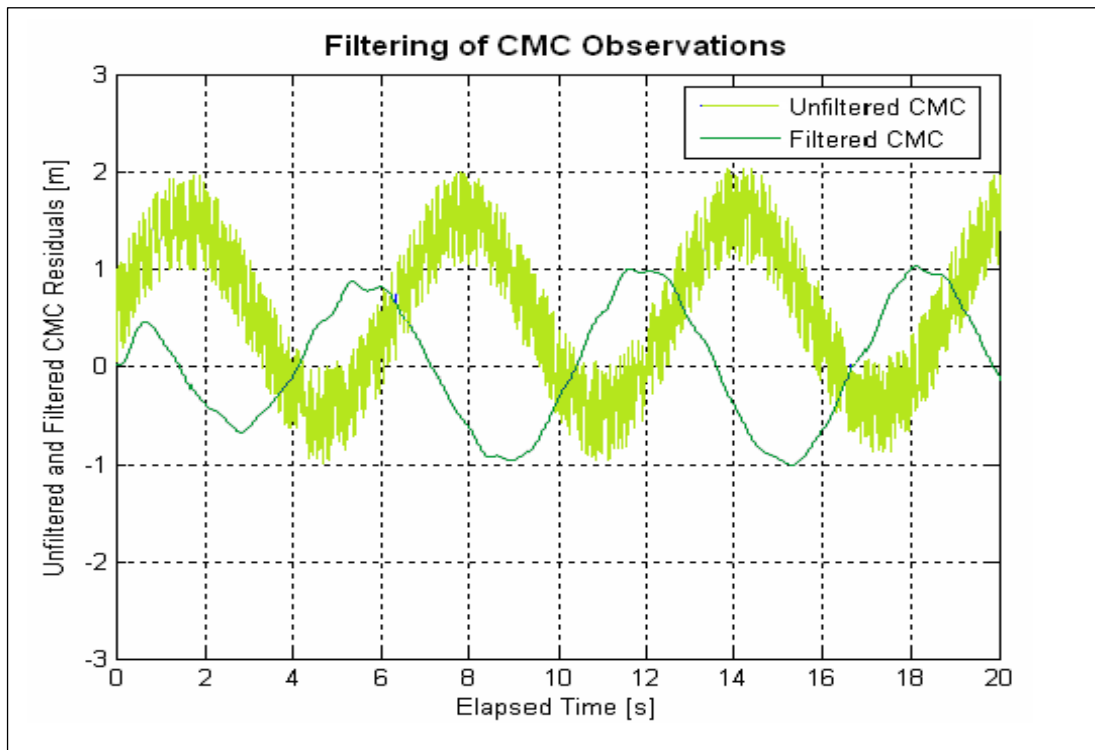


Figure 3.9: The 8th Butterworth filter for CMC observables.

Figures 3.8 and 3.9 illustrate the influence of the ionosphere, modeled as a polynomial of second order applying the sinusoidal waveform.

From these two figures, the effect of the thermal noise was observed and smoothed out, and the ionosphere has been removed through the filtration process. Figures 3.8 and 3.9 further illustrate the CMC observation filtration. On the other hand, the CMC observations are likely to contain a huge influence of phase and code noise, with the predominant effect represented by code noise. In that case, monitoring of the threshold is required, and the actual discriminator of the user monitor must be known so that code discriminator will be used to monitor the threshold [188]. The spectral analysis suggests the use of the CMC observables by transforming its observations into a frequency and analyzing the dominant fading frequencies in the spectrum. As a result, the influences of the multipath can be detected using the appropriate detectors and conforming threshold analysis.

3.8.6. Multipath Estimation Delay Lock Loop (MEDLL)

The MEDLL is the multipath mitigating technique that was developed around 1990, adhering to the basis of the Maximum Likelihood (ML) estimation method. The main aim of this method is to approximate the key multipath parameters such as relative multipath phase, amplitude, and multipath delay. MEDLL is also suitable for detection purposes due to its huge capacity for estimating the multipath parameters. The MEDLL is capable of using larger numbers of correlators during the sampling and further analyzing the peak correlation where the computation is carried out in time by the time center paradigm without requiring the information from the previous time [189]. MEDLL can be implemented on a real-time basis to detect and monitor the multipath; however, it has the huge downside of requiring a large amount of the correlator and a huge database for computation.

3.9. The techniques to mitigate the multipath signals

This section provides an impression of the most significant and popular multipath mitigation techniques, with a focus on the receiver's internal techniques. This chapter begins with the description of the most popular mitigating techniques, and the balance of the chapter provides the mitigation techniques for BPSK (1) for the recent GPD C/A code. For simplicity and the computation of the correlation function, 16 MHz is assumed for the pre-correlation bandwidth.

Most of the mitigating techniques apply the same principles as the multipath detection techniques. There are numerous multipath mitigating techniques globally that are dependent on the design of the whole navigation system, including the choice of component being used. Therefore, this section will briefly discuss a few multipath mitigating techniques.

3.9.1. The narrow correlation

This is the first approach and it has been introduced to the GPS receiver to mitigate the effect of the multipath. This is for code multipath mitigation. The narrow correlation indicates that, the chip spacing is less one between early and late code. The author in [188] suggested the chip spacing between early and late code must be $d = 0.1$ so that the discriminator function can build up.

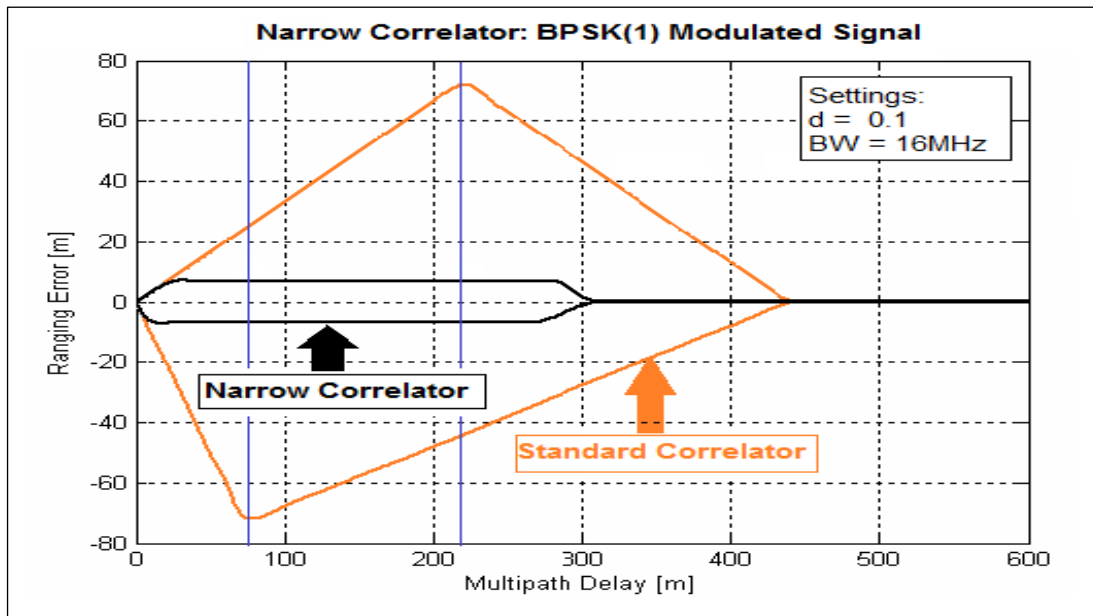


Figure 3.10: The Evaluation of the GNSS code discrimination and multipath signal error envelope for the chip rated 0.1 for the Narrow Correlator.

Figure 3.10 illustrates the differences between the standard and narrow correlator. Comparing the two correlating techniques, the effect and influence of the multipath signal can be mitigated by using narrow correlation techniques where the multipath signal is detected or suspected. The narrow correlator is sensitive to the chip spacing of $d = 0.1$, where the maximum multipath error is expected. The standard correlator has path delays of up to 1.5 chips and more thermal noise than the narrow correlator.

3.9.2. Special antennas

The special antenna for multipath mitigation is very popular because it influences the multipath signal before reaching the receiver. This approach is being proposed and considered in this thesis for further improvements. The choke rings are the simplest means of multipath mitigation if the special antenna is suggested. Choke rings have numerous concentric rings situated about the GNSS antenna. The Multipath Limiting Antenna (MLA) has two separate gain patterns [190]. The most popular antenna is the High Zenith Antenna (HZA) that is used for high-elevation satellites, and the signals for low-elevation satellites are dedicated to the separate antenna. Both antennas are connected to the different receivers, and the advanced processing unit is needed to combine the carrier and pseudo-range from the two antennas into one antenna called the virtual receiving antenna. This concept is anticipated to reduce the effect of the multipath, and the measurements of the noise in the signal are very low. The phased array antenna is made up of the several antennas arranged in an effective way to improve the gain patterns and other relevant parameters. The effective antenna pattern is reinforced in the desired direction and suppressed in the undesired direction. This technique is called beam forming as it allows the antenna to create the beam that will point in the direction of the satellite [190].

3.9.3. The double delta correlator

A double delta correlator is used for distinct discrimination of the codes that are formed by two correlator pairs. The double delta is also called a High-Resolution Correlator (HRC), and the general concept of the tracking principles is explained in [191]. There are two popular types of double delta correlator, the N^{th} derivative correlator and carrier smoothing. The discriminating function of the derivative correlator is built up by assuming that the N^{th} derivative correlator is the function and the undistorted signal is represented by the odd number of the N^{th} derivative correlator. The discriminating function is anticipated to be zero at the tracking point.

$$\text{PSR}_{\text{Smoothing}}(t) = \left[\frac{1}{Y_T} \right] \text{PSR}_{\text{raw}}(t) + \left[\frac{Y_T - 1}{Y_T} \right] \text{PSR}_{\text{predicted}}(t) \quad (3.45)$$

$$Y_T = \frac{S_{\text{sm}}}{T_{\text{data update}}} \quad (3.46)$$

where:

- t is the current time
- $PSR_{\text{Smoothing}}$ is the smoothed pseudorange in the specific time
- PSR_{raw} is the observed pseudorange in the specific time
- $PSR_{\text{predicted}}$ is the projected pseudorange derived from successive carrier observation of the previous cycle.
- S_{sm} is the smoothing time constant and the
- $T_{\text{data update}}$ is the time interval for data update.

3.9.4. Carrier smoothing

The carrier smoothing uses the smoothing algorithms to mitigate the multipath. The smoothed carrier pseudorange is obtained through the combination and processing of the code and carrier observations. Because the carrier observation is less affected by noise, this modelling approach is widely used for code observation [192]. Hence, the code multipath and noise are reduced significantly through the smoothing process. The analysis of the standardized deviation of the smoothed pseudorange carried out by rearranging and expanding (3.48) to be:

$$PSR_{\text{Smoothing}}(t) = \left[\frac{1}{Y_T} \right] PSR_{\text{raw}}(t) + \left[\frac{Y_T - 1}{Y_T} \right] PSR_{\text{smoothing}}(t - 1) + \Delta PSR_{\xi}(t) \quad (3.47)$$

From the law of the error propagation and equation (3.50), the standard deviation of the smoothed pseudorange is derived, and the observed pseudorange $PSR_{(\text{sm}, t-1)}$, the smoothed pseudorange $(t - 1)^{\text{th}}$ and pseudorange difference $\Delta PSR_{(t-1)}$ are not correlated. Hence, the variance of the smoothed pseudorange is:

$$\delta_{\text{sm},k}^2 = \left[\frac{1}{Y_T} \right]^2 \delta_{\text{raw}}^2 + \left[\frac{Y_T - 1}{Y_T} \right]^2 \delta_{\text{sm},t-1}^2 + \left[\frac{Y_T - 1}{Y_T} \right]^2 \delta_{\Delta PSR, t-1}^2 \quad (3.48)$$

The constant of smoothing period is much larger than time intervals for data update and the detailed results and analysis are found in [193].

3.10. The Maximum Likelihood Estimation of the amplitude, code delay and phase shift.

In this section, the model for multipath propagation estimation is proposed starting by the innovative analysis of the MLE for signals from four satellites. The MLE is the numerical approach of estimating the probability of the specific parameter through maximizing the function of likelihood. In this context the MLE algorithms estimate the multipath parameters originating from the space $\zeta_M = (\zeta_1 \dots \zeta_M)$ to maximize the Probability Density Function (PDF) $f_{PDF}(x) = \zeta_M$ for the specific set of data and pilot $x_{D/P} = (x_1, \dots, x_N)$ in the message. This section is set to estimate the key multipath parameters, the multipath phase, and amplitude and delay which are expressed using the numerical algorithms. Recalling the equation illustrated in equation (2.21) for baseband incoming signal, to estimate the additional multipath error, the new equation is presented in equation (3.49) below.

$$S_0(t) = \sum_{m+1}^{M_k+1} a_{k,m+1}(t) \varepsilon^{j\phi_{k,m+1}(t)} \xi_{k,m+1}(t - \tau_{k,m+1}(t)) + E_n(t) \quad (3.49)$$

where the:

- $a_{k,m+1}$ is the amplitude with the possibility of the new multipath component
- $\varepsilon^{j\phi_{k,m+1}(t)}$ is an exponential increase of the multipath components
- $\xi_{k,m+1}$ is the rotating direction of the satellite that contribute with multipath.
- $\phi_{k,m+1}$ is the phase with the possibility of the new multipath component
- $\tau_{k,m+1}$ is the delay with the possibility of the new multipath component
- E_n is the additive noise

The scientific contribution of this section is to analyze the limit of the theoretical accuracy of this approach and further use the MLE to estimate the Doppler shift and time delays in the multipath propagation signal. Hence, the values at $(m_k + 1)$ are expected to be diverse between satellite channels. Considering the concept of GNSS trilateration for the visible M_k satellites, the received GNSS signal is superposition of the transmitted signal from visible satellites propagating through the corresponding channel.

Each antenna of the GNSS user receives the different duplication of the signal represented in equation (2.21). However; those signals have the different phase depending on the antenna geometry and the arrival direction. The direction of signal arrival and antenna geometry are represented using the following vector model contain the spatial signature matrix for arrival direction G_k from the visible satellites, the diagonal vector of the amplitude A_k , the element related to the Doppler shifted and delayed narrowband signal envelopes that are sometimes scaled to mitigate the impact of the multipath and the additive noise.

$$x_k(t) = G_k A_k d_{k, \text{narrow channel}} + E_n(t) \quad (3.50)$$

The above equation is the general expression to define the vector of the observed signal ($x_i(t) \in \mathbb{C}^{N_i \times 1}$), the matrix that is related to the arrival direction, antenna array geometry and multi-constellation vector ($G_k \in \mathbb{C}^{N_k \times k}$), the amplitude vector along the diagonal side ($A_i = \in \mathbb{C}^{M_k \times M_k}$), the envelopes for Doppler shifted narrowband signals ($d \in \mathbb{C}^{M_k \times 1}$, $s_M(t - \tau_M) e^{j2\pi f_{M_1} t}$ and the expected noise inclusive of all other disturbing terms in the space ($w_k(t) \in \mathbb{C}^{N_k \times 1}$). The baseband signal function in equation (2.21) is considered to be the limited finite average power signal to demonstrate the reliability of the MLE and implies the analogue autocorrelation. The Doppler spread is the additional effect that modifies the satellite transmitted signal when is captured in the manifold antenna of the GNSS receiver. Hence, the relative motion between the GNSS transmitter and receiver causes the shift in the received signal. This condition of frequency broadening was discovered long time ago and the details are reported in [194]. Such Doppler deviations are encompassed in equation (3.52) as the phase of the linear component. The propagation channel of the single satellite is expressed in equation (3.53). Equation (3.53) used for the purpose of analysis and is anticipated to be valid because is independent to the nature of satellite communication links.

Furthermore, the additive noise term is neglected, the carrier frequency for navigation data is f_{cN} and the multipath is assumed to be equal to one considering the LOSS from propagation channel.

$$(S_{TN}(t)e^{j2\pi t f_{cN}}) = a_k(t)s_T(t - \tau_0)e^{j2\pi(t - \tau_0)f_{cN}} \quad (3.51)$$

In that case, the effect of the Doppler shift is modeled using the shift of the ordinary frequency and this is known as the hypothesis of the narrowband signal model [195]. In order to illustrate the stability and reliability of the MLE, the baseband signal is considered and is assumed to have limited finite average power and implies the analogue autocorrelation.

$$X_{NSS}(\tau) = \lim_{K_i \rightarrow \infty} \frac{1}{K_i} \int_{N_k}^1 S_T(t - \tau_i) S^*(t) dt \quad (3.52)$$

From equation (5.19) N_k is satisfying the Nyquist criterion and this concept is extended to incorporate the Doppler shift and expressed as:

$$Y_{NSS}(\tau_k - \tau_k) = \lim_{T \rightarrow \infty} \frac{1}{T} \sum_T s(kT_s - \tau_i) s^*(kT_s - \tau_k)^1 \quad (3.53)$$

The algebraic matrix form is used to compute the time delay of each antenna in the multi constellation context and expressed as:

$$\xi_M = e^{j\pi XY} \quad (3.54)$$

The ξ_M matrix function depends upon the geometry of the antenna type and design, and this is considered to be the unique spatial signature and the wavenumber matrix $x \in Y^{M \times 3}$ is defined as:

$$x = \begin{bmatrix} \cos(\theta_1)\cos(\sigma_1) & \sin(\theta_1)\sin(\sigma_1) & \sin\theta_1 \\ \vdots & \vdots & \vdots \\ \cos(\theta_M)\cos(\sigma_M) & \sin(\theta_M)\sin(\sigma_M) & \sin\theta_M \end{bmatrix} \quad (3.55)$$

In equation (3.54), the element of positioning is normalized adhering to half units of the wavelength in accordance to local navigation and positioning systems. Hence, equation (3.55) further agrees that, the direction of arrival is contained. For multi-constellation, the transpose of $G_i \in \mathbb{C}^{N_k \times M_k}$ is used and anticipated to be:

$$G_T = G^{T_{sa}} * G_i \in \mathbb{C}^{N_k \times M_k} \quad (3.56)$$

The transpose of G_i is for the impinging signal is taken along with sampling time T_{sa} to satisfy the Nyquist criterion. The sampled data over time is using the same pattern as equation (3.56) and expressed as:

$$x_i(t) = C^T \zeta(t, \tau) + E_n(t) \quad (3.57)$$

where:

$$\tau = (\tau_0 \dots \tau_{k-1})^{T_{sa}} \quad H_k * 1 \quad (3.58)$$

$$C^T = (a_0 \dots a_{k-1}) \quad M_i * H_k \quad (3.59)$$

$$\zeta(t, \tau) = s(\delta T_s - \tau_0) \dots s(\delta T_s - \tau_1) \dots s(\delta T_s - \tau_{k-1}) \quad H_k * \quad (3.60)$$

This section is concern about incorporating the concept of new path detection into CSD multipath mitigating technique. According to [127], the Galileo and GPS are interoperable, and the GPSL5 signal and GalileoE5a signal are sharing the same frequency. In this study, we exploit such advantages to improve the reliability of the GPS systems using the advanced capabilities of the GalileoE5a. Hence, the collected signals from various satellites are grouped together and expressed as:

$$X_k = [x_k(1) \ x_k(2) \ \dots \ y_k[N]] = C^T \zeta(\tau) + \xi \quad (3.61)$$

Where the $\zeta(\tau) \in \mathbb{C}^{k \times N}$ and $\xi \in \mathbb{C}^{m \times N}$ are identically and support P_k in terms of data filtration for multi – constellation in structured multi antenna environment. Equation (3.62) and (3.63) are satisfying the assumption of the narrowband hypothesis and these equations are appealing to the common signal processing problems that are common to many multi-signal conditions. Hence, we assumed that, the time that is required for the various signals to be grouped must be smaller than the inverse bandwidth in order to address such problems relating to multi signal processing time. To develop the algorithms and procedure of estimating the amplitude, code delay and phase shift, we recall equation (2.11) used to define the monitoring of the multipath signal along the propagation channel and further recall equation (3.5).

Following is the flow chart that briefly explain the concept of the MLE from the input signal to the end user when estimate the amplitude, code delay and phase shift in the context of GNSS multipath signal.

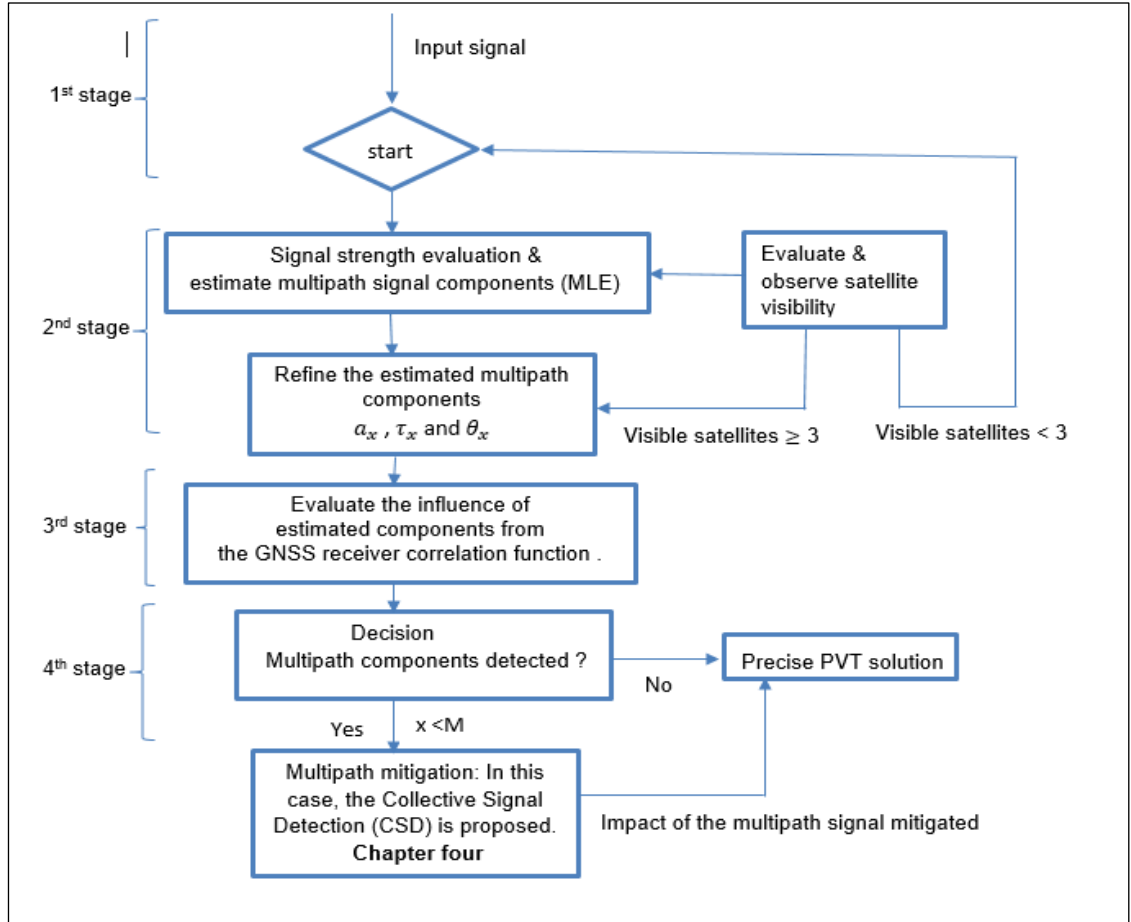


Figure 3.11: The flow chart of the proposed MLE of the amplitude, code delay and phase shift.

The numerical explanation of Figure 3.11 is following:

1st step

$$s^{(X)}(t) \text{ to } s(t) = \sum_{x=0}^M \alpha_x \delta(t - \tau_x) e^{j2\pi f_{D,x} t + j\theta_x} \quad (3.62)$$

2nd step

Determine the comprehensive value of $s^{(m)}(t)$ and estimate the signal parameter α_x , τ_x and θ_x

Recap: α_x is amplitude, τ_x code delay and θ_x phase shift

3rd step

Re – evaluate the signal parameters α_x , τ_x and θ_x

The x input denotes the GNSS satellite and M denote the multipath, the assumption made is $x = M$

Hence, new algorithm will be:

$$s^{(M)}(t) \text{ to } s(t) = \sum_{x=0}^M \alpha_M \delta(t - \tau_M) e^{j2\pi f_{D,M} t + j\theta_M} \quad (3.63)$$

4th step

If changes not detected in α_x , τ_x and θ_x , repeat second step

If changes in α_x , τ_x and θ_x are detected, and $x < M$ and M continue to upturn, the desired multipath has been detected.

3.11. Summary and conclusion

Numerous models are used to characterize the GNSS multipath signal propagation that have been discussed and examined to explore their realistic contribution to the analysis of the GNSS multipath. A comprehensive analysis of the multipath has been carried out in this chapter, starting from the definition of the data transmission channel. It has been noted that, in the existence of the multipath signal, the wideband model for transmission is widely adopted for the transfer function. Hence, the receiving antenna needs to be modelled to accommodate the issue of multipath signals, the direct and echo signals of which are the fundamental objective of this research. In chapter four of this research work, the collective signal detection technique is introduced to address the issue of signal multipath. This approach is to mitigate the carrier multipath in linear combinations.

CHAPTER FOUR

The Combined Signal Detection of the Diverse GNSS signals to mitigate the carrier multipath in linear combination

The previous chapter discussed the various techniques for mitigating the multipath and further estimated the changes in amplitude, code delay, and phase shift caused by the presence of the multipath component. In this chapter, we present the concept of the Combined Signal Detection (CSD) technique to alleviate the impact of the multipath signal estimated in Chapter 3. The CSD is the most capable technique in terms of signal acquisition to calculate position, velocity, and time in challenging locations. The CSD technique is based on the concept of multiple frequencies among the numerous GNSS constellations, in this case, the GPS and Galileo constellations. The concept of CSD in multi-frequencies conditions is briefly introduced in this chapter, and the rest of the chapter provides a comprehensive analysis of the signal degradation sources in GNSS receivers that are capable of processing the multi-GNSS signals.

4.1. Background

In previous chapters, the structure GNSS signals and multipath mitigation techniques were reviewed. Such discussions concluded that most of the currently used multipath mitigating techniques are still unable to mitigate the multipath in cases of residual multipath error to the extent where high accuracy is required. The current networks of GNSS constellations make multi-frequency measurements available. The multi-frequency technique is utilized to mitigate the errors in the ionospheric region. The multiple frequencies form the linear measurements of the combined frequencies. Despite the fact that multipath error is strongly dependent on GNSS frequency, current techniques focus on a single frequency level, this is the case. The GNSS multipath affects both carrier phase and pseudorange measurements. However, the effect of the GNSS multipath in pseudorange is higher than the measurements of the carrier phase. To characterize and analyze the impacts of GNSS multipath in urban areas, the signal noise ratio (SNR) and elevation angles are used.

The carrier multipath errors have a dispersive nature; hence the effort of this thesis is to mitigate the multipath errors in their linear combinations.

The urban city makes extensive use of GNSS receivers embedded in smart phones and tablets to form a business market known as location-based service. Hence, GNSS users expect a high level of accuracy. However, the urban environment is the one location that generates difficulties in the response of the GNSS signals. Hence, the GNSS signals are not well captured in urban areas due to the reflection that is caused by the tall buildings. The acquisition of the GNSS in difficult environments is a difficult task because the signal power is too low. Therefore, it is difficult to acquire and track all signals separately. The GNSS signals are affected by numerous factors (interference, masking, jamming, and multipath). The concept of the CSD is that the multipath signals will be acquired and tracked collectively. Furthermore, the strong ones will assist in the detection of weak signals from satellite. The CSD is dependent on GNSS signal acquisition techniques. Hence, a thorough analysis of signal acquisition is mandatory before applying the proposed methodology.

4.2. The working Principle of Collective detection of the GNSS multipath signals

The combined detection of the multipath signal strongly depends on the assistance of GNSS data. Hence, the GNSS data used in this research is IMF, or the concept of multi-frequencies in line-of-sight combination. The simple idea of adopting collective detection is to utilize the strong signals to detect the weak signals in a multi-satellite environment. The concept was boosted by the progress made in advancing the interoperability between GPS, Galileo, and BeiDou.

The main idea of proposing the CSD was to conduct the GNSS signal acquisition over numerous iterations and refine the search for strong signals to obtain accurate data. According to [02], the CSD is capable of improving signal detection and dB levels. However, the CSD requires intensive computational work to accommodate all candidate points.

Hence, numerous approaches were suggested to resolve the issue of computation. [03] proposed using a correlogram at the start of the signal and a satellite search to accelerate detection. Because most of the new GNSS constellations, including the augmentation systems, were still in development,

this technique required the evaluation of the correlogram of all visible satellites from a specific GNSS constellation (e.g., the GPS constellation only). Once the satellites are identified, they are then combined into a common clock bias domain to create the projected position and time domain. Furthermore, the correlation values of the CSD are pre-stored in the database, which requires large database memory. In cases where the sampling frequency is high, the Fourier Fast Transform (FFT) is used to evaluate the correlogram of each satellite in view. Hence, this thesis focuses on the CSD and introduction of IMF from the multi-GNSS constellations (e.g., the GPS and Galileo constellations). In the CSD approach, the GNSS satellite signals are acquired collectively, with the search for code delay being mapped to the receiver clock bias. Therefore, the projection of the code phase for the signal is performed differently, adhering to pseudorange. The thorough Doppler search becomes less crucial as it is determined by the assistance data. The equations for convectional signal acquisition is represented in equation (4.1) and equation (4.2), respectively. For convectional signal acquisition, the correlated input signal for local duplicates and the correlating power for conforming satellite x is expressed as:

$$S_{Acqu}(\tau_x) = |S_\tau \hat{k}(\tau_x)|^2 \quad (4.1)$$

$$= |a_x k_x(\tau_x) + n_x \cdot k_x(\tau_x)|^2 \quad (4.2)$$

The baseband complex signal input and additive noise is represented in equation (4.3).

$$S_\tau = \sum_{x=1}^{N_x} a_x k_x(\tau_x) + n \quad (4.3)$$

In equation (4.3), the $k_x(\tau_x)$ presents the signal vector of the satellite x τ_x is the signal code phase, N_x is the number of the satellite in view or visible satellites and n is the additive noise component. In the convectional signal acquisition presented in (4.1) and (4.2), the $k_x(\tau_x)$ and τ_x represent the convectional signal replica and theorized signal code delay for k satellite.

In convectional signal acquisition, the peak point of the signal correlation is calculated as the code delay of signal from each satellite. The conventional signal acquisition estimates the peak position of the correlation as the code delay of each space satellite.

Hence, the estimation of the additional parameters is denoted by $\hat{\gamma}$. These vectors include three parameters in the receiver estimation methodology and position (u_r, e_r, n_r) and these are parameters of common clock bias b_r estimation. Adhering to the proposed CSD approach, the estimation of the navigation parameters is carried out through the noncoherent summing of the correlating power for all visible satellites. This is also computed for conventional acquisition to be performed in clock and position bias domains. Hence, the numerical expression will be,

$$S_{\text{CSD}}(\tau_x) = \sum_{x=1}^{N_x} |S_{\tau} \hat{v}(\hat{\tau}_x(\hat{\gamma}, \Psi))|^2 \quad (4.4)$$

Where Ψ signifies the satellite position vector.

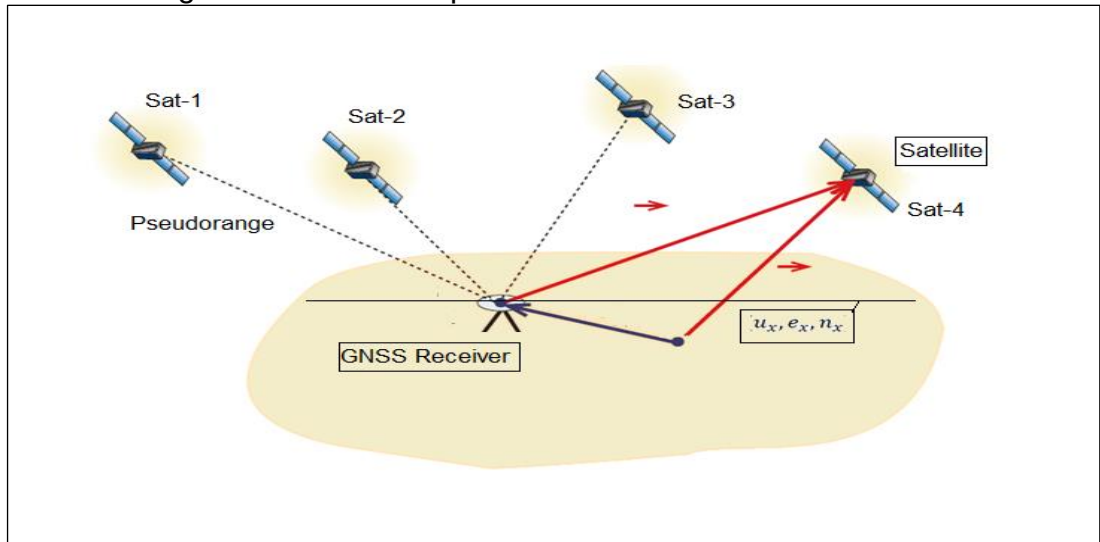


Figure 4.1: Forecast of the GNSS clock bias domain in CSD.

The CSD strongly depends upon the concept of the Earth-Centered Earth-Fixed (ECEF) coordinates of the satellite in view with the reference of (u_x, e_x, n_x) . Hence, the pseudorange measurements for the corresponding satellite x is obtained using the nonlinear relationship between the code delay and receiver's position.

$$p_x = \sqrt{(e_x - e_r)^2 + (n_x - n_r)^2 + (u_x - u_r)^2} + c \cdot \Delta\beta \quad (4.5)$$

where:

- $c \cdot \Delta\beta$ denote the user clock bias

The CSD technique combines the received signal power from all visible satellites adhering to dual frequencies.

4.3. Methodology of CSD application in GNSS signals:

Combining GPS and Galileo – multiconstellation

The technique of the CSD uses the acquisition search grid that is defined by the 3D position coordinate. The 3D positioning coordinates are used to represent the numerical distance between the GNSS receiver and the space satellites. Equation (4.5) is used to project the GNSS code delay in the correlator output based on the user's clock and position bias domain. Recalling, Figure 1.3, the mapping of the signal code delay to the position and clock bias to the domain user is presented adhering to the pseudorange measurements provided by the reference station. The pseudorange measurements seen by the user for the satellite x are:

$$\rho_{CS,x} = \rho_{GNSS R,x} + \Delta\rho_x \quad (4.6)$$

There are some uncertainties regarding the space related applications, hence the clock bias and initial position is cantered and defined in the initial knowledge. The pseudorange seen by the GNSS receiver $\rho_{GNSS R,x}$ is situated at the center search space for the satellite x . Hence, the offset range from the GNSS receiver is expressed in terms of clock bias and direct position.

For the hypothetical location and clock bias, the pseudorange is converted into a comparable code phase as illustrated in Equation (4.7).

$$\hat{\tau}_x = \frac{[\rho_{RS,x} + \Delta\rho_x(\Delta U_u, E_e, N_n, B_b)] c.T_{code}}{c.T_{code}} \cdot N_{c/p} \quad (4.7)$$

Where the:

- $\hat{\tau}_x$ is the code phase in estimation for the visible satellite x
- $c.T_{code}$ is the spreading code for GPS signals (the GPS L-1 C/A code) in the modulo in operation of $\hat{\tau}_x \in [0, N_{c/p} \pm 1]$
- $N_{c/p}$ is the number of code chip over the given period of time.

The output of the correlation value corresponding to visible satellites is projected from the code phase and the clock or direct position bias. Under this view, the code phase is calculated by:

$$C_{phase}(\hat{\tau}_x) = |S_{cp}(\hat{\tau}_x)|^2 \quad (4.8)$$

Where the:

- $S_{cp}(\hat{\tau}_x)$ is the correlation output that correspond to the phase code.

This detection matrix are used for simulation to represent the correlation output that plays crucial role in signal processing of the GNSS receiver under the purpose of multiconstellation and signal combining. The collective detection of the signal from multiconstellation is achieved through the function of the imaginary coordinates and the clock bias.

4.4. Methodology and data collection

This section provides the methodology of implementing the CSD technology and the data collection for simulation.

4.4.1. Architecture of the proposed hybrid scheme

The correlation block of the proposed CSD methodology requires high resolution in the final iteration. Hence, the high resolution is avoided in the first alteration, and the correlation of one sample per chip is utilized. The individual detection metric of all visible satellites and the CSD metric are calculated to obtain an estimate of the user position and code for each satellite in view. It must be noted that we need at least three satellites to be visible to the receiver. This approach is hybrid, which means it accommodates the visibility of satellites from different constellations. In this case, the correlation for estimated code is performed with four samples per chip resolution and the code phase is shifted with sampling period T_s for each correlation point.

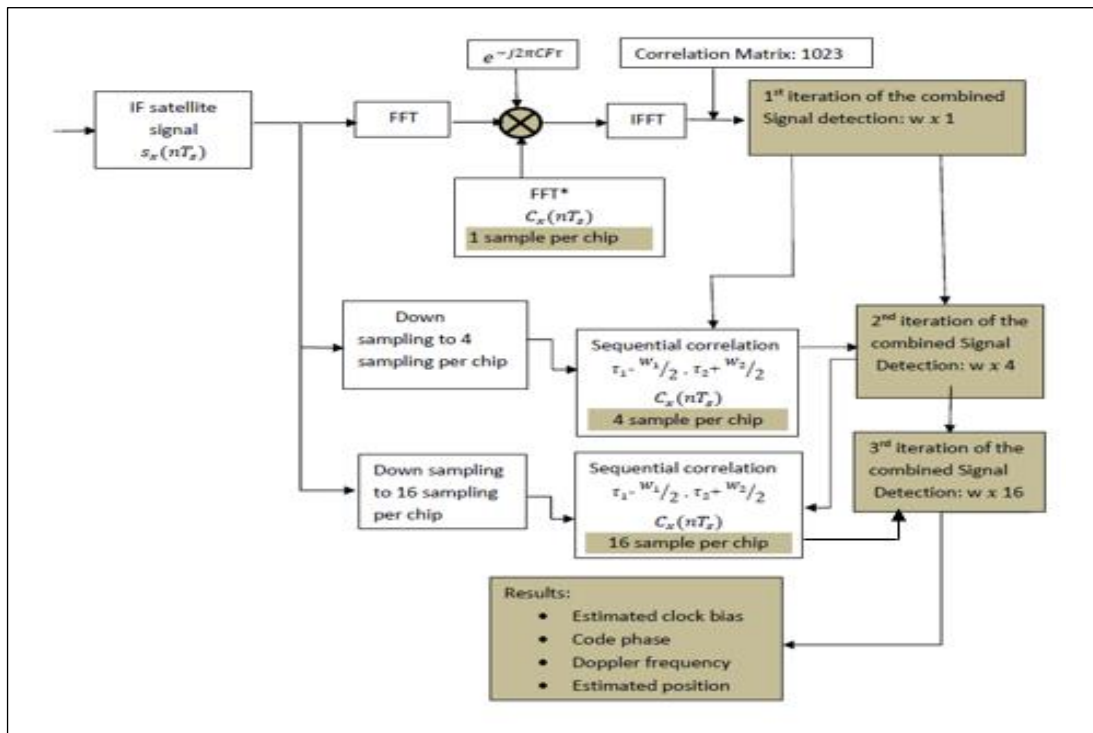


Figure 4.2: The block illustration of the CSD and data processing

The implementation of the proposed CSD approach in Figure 4.2, implicates the detailed flowchart of the signal processing that conform to the CSD method. In Figure 4.3, the flowchart to describe the detailed three iteration steps is shown. In the beginning of the iteration, there is no need of the high or better resolution and the correlation of one sample per chip is fair enough. The position domain resolution is assumed 1km and the individual detection for each satellite in view have the correlation value conforming to the predictable signal Doppler frequency and code phase.

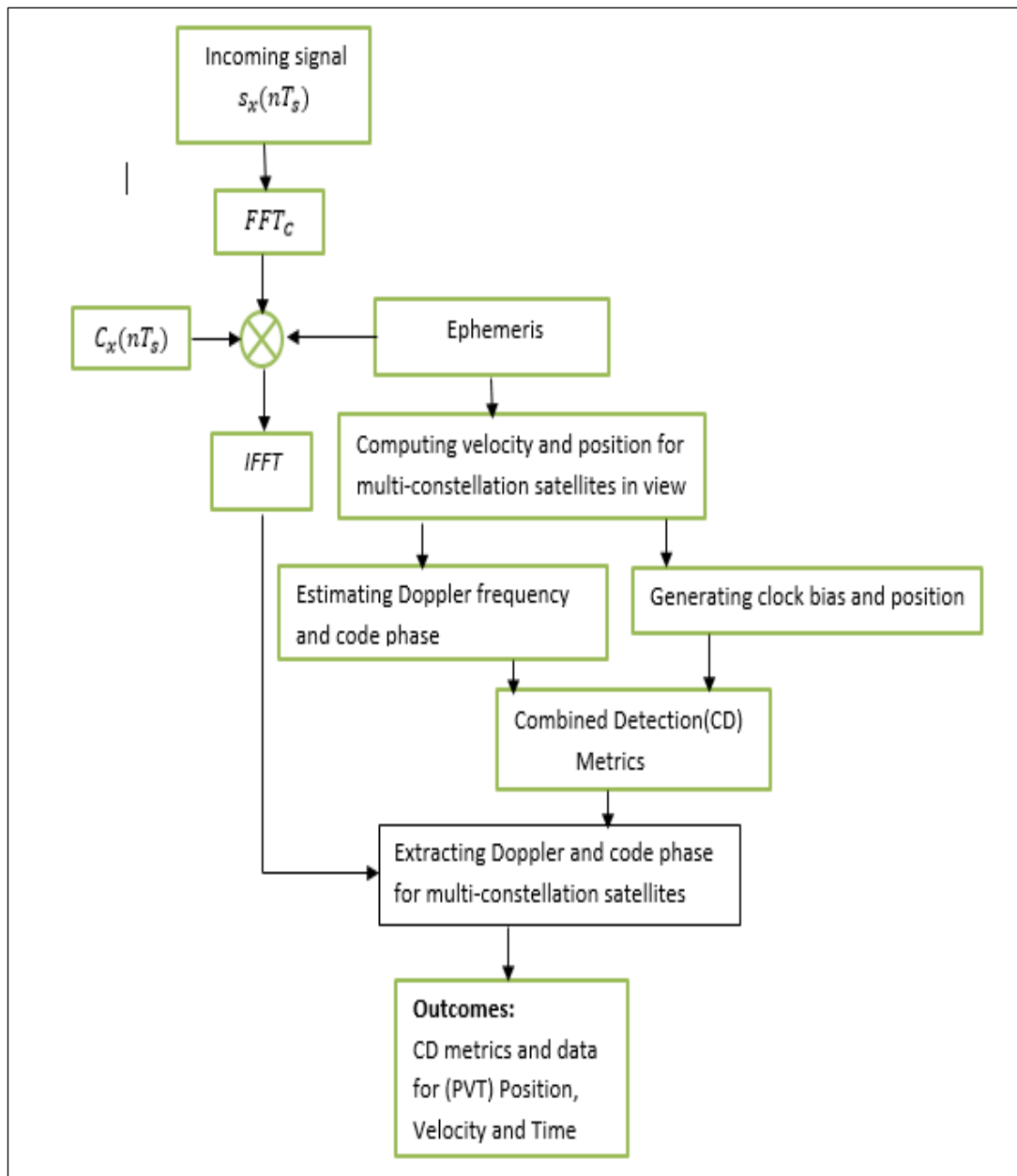


Figure 4.3: The flowchart of the CSD iteration steps.

In second iteration: In this case, the new correlation using sequential search is adopted and the code phase is performed using the four chips per resolution. Hence, the sequential search is carried out between $\tau_1 - W_1/2$ and $\tau_2 + W_2/2$ and both shifted by the sampling time. The detection of the visible satellites corresponds to the estimated code phase that is within the region of $W/2$ from both sides. The fixed Doppler frequency is estimated in the first correlation block. Hence, the CSD matrix is calculated by adding all correlation values for visible satellites and further establish the domain position of 100 m.

The establishment of the 100 m domain position helps to achieve the medium search for grid resolution. Therefore, the new code search is estimated for each satellite in view from the CSD correlogram metric. The CSD correlogram metric is required for the third iteration. In the last iteration, the new correlation is performed using the sequential search method as shown in both Figure 4.2 and 4.2. In this case, the finest estimate is required; hence, there are 16 samples per chip that are used.

4.4.2. The Complexity analysis

The critical aspect is to have a good estimate of the code phase during the autocorrelation process and further optimize the calculating burden. This approach reduces the need for advanced data processing since it uses the multi-iteration approach. In this case, the CSD approach is used with the phase code resolution of one sample per chip. The numerical operations of all stages are:

$$\begin{aligned} \text{First to last stage_operation} &= N + \mathcal{R}_{F_L}[\text{FFT}(M)] \\ &\mathcal{R}_{F_L}[\text{FFT}(M)] + \mathcal{R}_{F_L}[\text{FFT}(M)] \end{aligned} \quad (4.9)$$

The equation in (4.9) presents the iteration from the first stage to the last stage, and the correlation matrix is computed in the second iteration using the sequential search approach. In the first iteration, there are four samples per chip. The concept of the sequential search is to ensure that we do not lose the correct phase code of the GNSS signal. The correlation output of the process will be the results of the incoming signal with the shifted code.

In order to obtain the expression of the standard covariance and deviation from the effect of the correlator output, the derivative model of the correlator output is required. Hence, a similar concept is further used in the chip domain to obtain the bin deviation standards. The Correlator Output Derivatives Model is

$$I_{CORR} = \sqrt{\frac{P_{CORR}}{2}} R_{CORR}(\varepsilon_\tau) D_{bit} \frac{\sin(\pi \varepsilon_{CF} T_{int})}{\pi \varepsilon_{CF} T_{int}} \cos(\varepsilon_{CPD}) + n_p(\varepsilon_{CPDE}) \quad (4.10)$$

$$R_{CORR} = \int_{-\infty}^{+\infty} I_{RF}(f) S_t(f) S_{Local}^* e^{2\pi C F \tau} df \quad (4.11)$$

where the:

- R_{CORR} is the correction function for filtered GNSS signal code and the local replica
- ε_τ is the measure of group delay per second
- $\pi \varepsilon_{CF}$ is the carrier phase Doppler frequency
- D_{bit} is the sign of GNSS data bit
- ε_{CD} is the carrier phase delay
- n_{IPC} is the noise of the in phase signal components.
- ε_{CPDE} is the carrier phase Doppler error
- I_{RF} is the front-end filter impulse of the Radio Frequency.
- S_t is the nominal GNSS signal filtered at front end
- S_{Local}^* is the local GNSS signal replica

Following are the inferences of these mathematical expressions:

- It has the comparable effect to apply a filter on a multipath signal or to apply the filter on the original GNSS signal and the multipath replica independently.
- It has the comparable effect to apply a filter on a correlation function of the multipath signal or to apply the filter on the ideal correlation function of the original signal and the local replica separately.
- It has the similar impact to apply a filter on the incoming GNSS signal or to apply it on the correlation function in the processing.

4.4.3. GNSS signal Acquisition of the CSD technique

This step determines whether the received GNSS components are visible enough to be processed by the GNSS receiver. This is done by generating the replica signal locally and correlating it with the received GNSS signal.

Based on Figure 4.2, the output of the sequential correlator also provides the receiver with the estimation of the Doppler shift, amplitude changes, and code delay for further processing. Hence, the concept of GNSS acquisition in CSD in Figure 4.2 is done sequentially to test all probable combinations of the Doppler shift, code delays, and PRN codes of the incoming signal. The GNSS correlation is performed between the incoming and locally generated replica signals, and the responses of the Doppler frequency and delay are monitored. Hence, the GNSS receiver needs the detailed information of the satellite in view during the correlation, and such data are obtained in the incoming signals.

Testing algorithms:

The equations are tested and simulated to directly concise to Equation (2.1) where the baseband incoming signal is illustrated.

The estimation of the Doppler frequency:

$$\hat{f}_d = \hat{f}_{dx} + \hat{f}_{\delta x} \quad (4.12)$$

Estimation of the code delay: from equation (4.7)

$$\hat{t}_x = \frac{[\rho r_{s_x} + \Delta \rho_x] c T_{code}}{c T_{code}} \quad \text{Recalling equation (4.7)}$$

Time Delay Estimation of Multiple Replicas of a Signal

The goal pursued here is to present an asymptotically efficient approximation of the time delays of multiple signal replicas of a known baseband signal received with complete autocorrelation.

Conditions where equation (4.8) and (4.9) are tested.

Individual detection metrics:

$$S_x(\hat{t}_x, \hat{f}_{dx}) \quad (4.13)$$

CSD metrics in positioning domain: 1st step

$$\sum_x |S_\delta(\hat{t}_x, \hat{f}_{dx})|^2 \quad (4.14)$$

$$C_x(nT_s) \dots \dots \dots (1) \text{ One sample per chip} \quad (4.15)$$

Sequential correlation search for second step: four samples per chip

$$\text{LHS} = \tau_1 - W_1/2, \text{ RHS} = \tau_2 + W_2/2 \quad (4.16)$$

The sequential search also applies the following code word bit to the incoming signal sample per chip:

$$C_x(nT_s) \dots \dots \dots (4) \text{ Four sample per chip} \quad (4.17)$$

CSD metrics in positioning domain: 2nd step

$$\sum_x |S(\hat{\tau}_x, \hat{f}_{dx})|^2 \quad (4.18)$$

Sequential correlation search for third iteration: 16 samples per chip

$$\tau_1 - w_1/2, \tau_2 + w_2/2$$

$$C_x(nT_s) \dots\dots\dots 16 \text{ sample per chip} \quad (4.19)$$

CSD metrics in positioning domain: 3rd step

$$\sum_x |S(\hat{\tau}_x, \hat{f}_{dx})|^2 \quad (4.20)$$

4.4.4. Satellite Data collection

The data was collected in two different locations; all locations have the full visibility of the Galileo and GPS constellations. Figure 4.3 illustrates the skyplot of the visible satellites in the view of the GNSS receiver that is capable of multi-constellation and multi- frequencies.

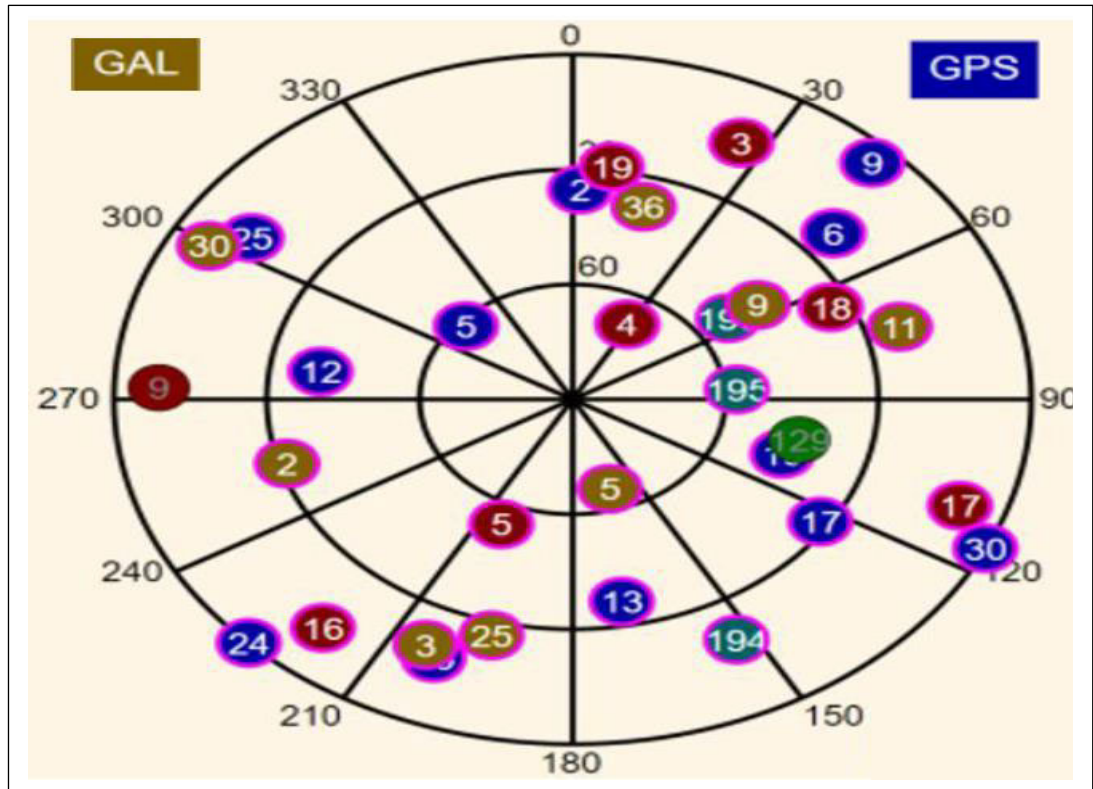


Figure 4.4: The illustration of the Galileo and GPS satellite visibility (skyplot).

The GNSS receiver used here is i90 Pro Receiver IMU RTK GNSS Receiver that is capable of Wi-Fi communication, UHF communication ranging between 410 to 470 MHz and integrated with 4G modem. In terms of accuracy, the receiver has the crucial followings specifications: Cold start: < 45 s, Hot start: < 10 s and Signal re-acquisition: < 1 s.



Figure 4 (a): Flat surface with no signal obstruction
GPS receiver, only capable of processing GPS signals



(b): Flat surface with minimum signal Obstruction
GPS receiver

Figure 4.5: Data collection (free and minimum signal obstruction).



(a): Flat surface with minimal signal obstruction
GPS receiver only



(b): Flat surface with maximum signal obstruction
(GPS+Galileo signals), combined detection of
the signal (Multiconstellation GNSS receiver)
for indoor application

Figure 4.6: Data collection (minimum and maximum signal obstruction).

4.4.5. GNSS gLAB simulation and analysis

In this section, there are two software packages used to analyse the GNSS signal processing: the gLAB and Matlab. The gLAB tool is used to perform accurate modelling of the GNSS observables, also known as the carrier phase and pseudorange measurements. The functionality of the gLAB includes a detailed database for processing the GPS and Galileo constellations.

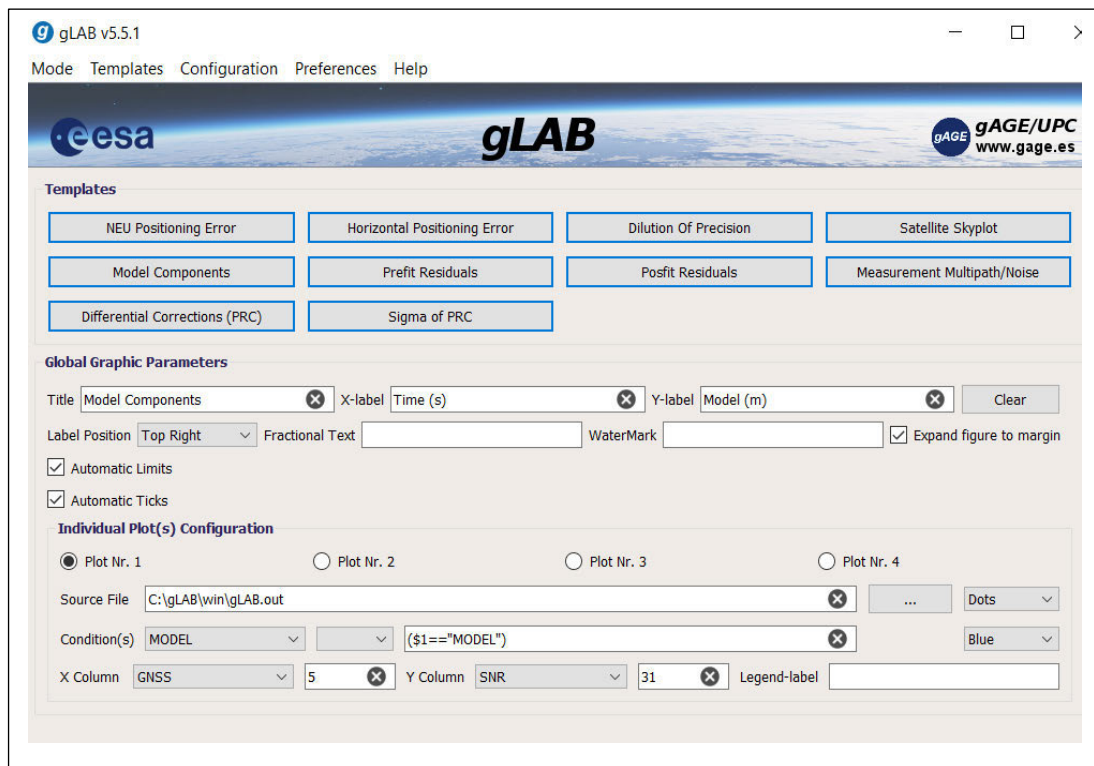


Figure 4.7: The main menu page of the gLAB software for modelling.

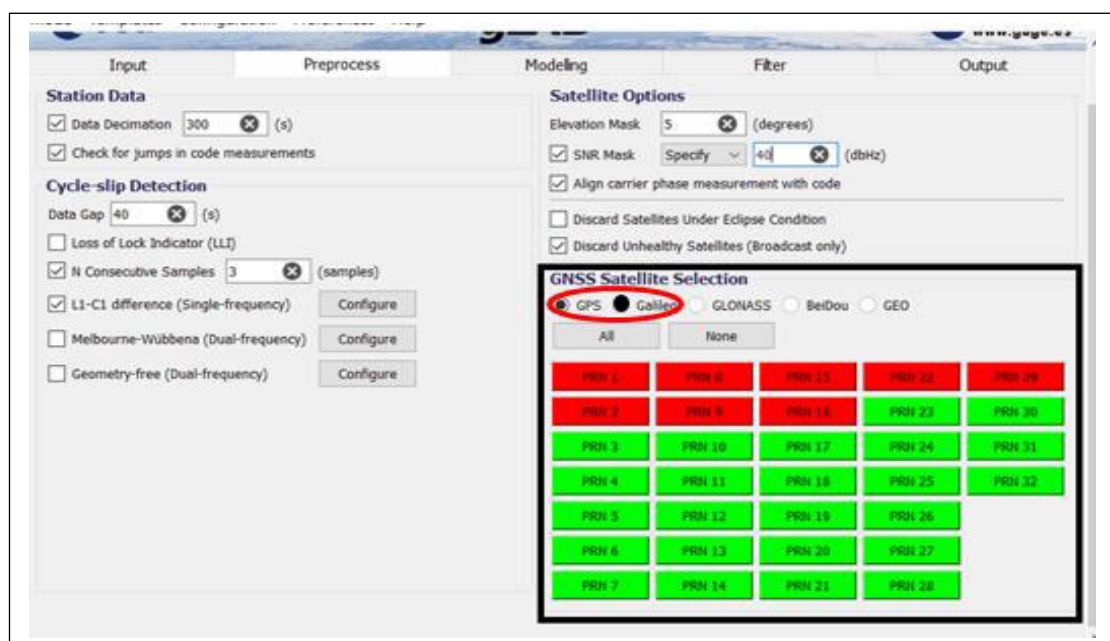


Figure 4.8: Satellite constellation selection and process configuration.

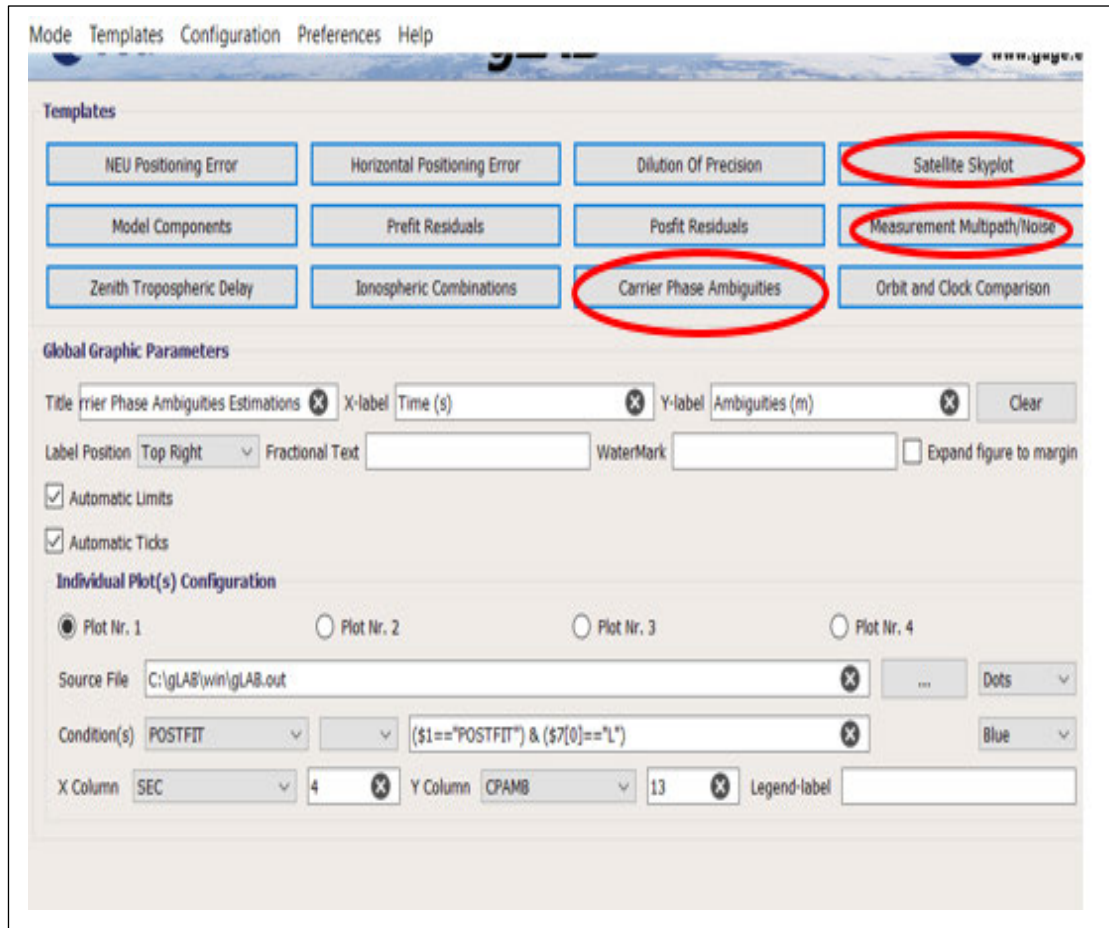


Figure 4.9: The view of the carrier phase ambiguities, skyplot of visible satellite and measuring the noise or multipath signal.

The analysis of the GNSS signals with respect to the parameters of the digital GNSS receiver is vital to investigate the impact of the GNSS signal Threat Models (TMs). The threat models denoted the phenomenon that is likely to occur at the space level if the satellite itself is faulty and is inducing distortions and replicas for every emitted signal. Hence, the signal quality needs to be tested to detect the satellite errors. Such GNSS testing and monitoring is required for GNSS users that require high accuracy, integrity, and availability. Figures 4.8 and 4.9 are the analysis menus of the GNSS signal in the gLAB software; Figure 4.10 is where the satellite constellations and PRN codes are selected; in this case, we used both GPS and Galileo constellations and eight PRN codes marked red. An approach to investigating the threat models that contribute to multipath will ease the correlation function of the GNSS in locations with weak satellite signals.

The screenshot displays a software interface for configuring GNSS inputs, organized into five tabs: Input, Preprocess, Modeling, Filter, and Output. The 'Input' tab is currently active.

Station Data

- ☒ Data Decimation: 300 (s)
- ☒ Check for jumps in code measurements

Cycle-slip Detection

- Data Gap: 40 (s)
- ☐ Loss of Lock Indicator (LLI)
- ☒ N Consecutive Samples: 3 (samples)
- ☐ L1-C1 difference (Single-frequency) [Configure]
- ☒ Melbourne-Wübbena (Dual-frequency) [Configure]
- ☐ Geometry-free (Dual-frequency) [Configure]

Melbourne-Wübbena Cycle-slip Detection Parameters

- Initial stdDev: 2 (m)
- Minimum stdDev: 0.8 (m)
- Window: 300 (s)
- k-factor: 5
- N-sample: 2 (epochs)

Satellite Options

- Elevation Mask: 5 (degrees)
- ☐ SNR Mask
- ☒ Align carrier phase measurement with code
- ☐ Discard Satellites Under Eclipse Condition
- ☒ Discard Unhealthy Satellites (Broadcast only)

GNSS Satellite Selection

- ☒ GPS ☐ Galileo ☐ GLONASS ☐ BeiDou ☐ GEO
-

A grid of 32 buttons, each labeled 'PRN' followed by a number from 1 to 32, is displayed below the selection options. All buttons are currently highlighted in green.

Figure 4.10: The configuration of the GNSS inputs for processing.

In Figure 4.10, the GNSS data processing entries for GPS constellation are configured that include the aligning of the carrier phase with GNSS code and elimination of the unhealthy signals.

4.4.6. Challenges in weak GNSS signal acquisition

It is very challenging to calculate the GNSS parameters in locations with weak signals, and this is considered to be a limitation of the high-sensitivity techniques, either non-coherent or coherent integration. Hence, in Figure 4.10, the mapping for dual frequency in glAB software is illustrated. This is the cross-correlation of weak and strong signals to mitigate the effect of data messages and code Doppler. The detection and processing of the weak GNSS signal is difficult in many applications, and the Code Division Multiple Access (CDMA) modulation is recommended for such conditions. In the case of the limited dynamic range of the GPS C/A code, dealing with the acquisition of weak signals and cross correlation proves challenging. The cross correlation is highly used in GPS signal and it influences the Frequency Division Multiple Access (FDMA) of the Russian system called Glonass. If the GPS L-1 C/A signal is without the Doppler and the proper signal alignment, there are three probable values in the correlation of that signal, namely:

- First: $1/1023$ and the log scale of -60 dB autocorrelation
- Second: $63/1023$ and log scale of -24.21 dB autocorrelation
- Third: $-65/1023$ and the log scale of -23.94 dB autocorrelation

There are radical changes in the correlation and acquisition if we consider the Doppler frequency and the autocorrelation values can reach the maximum set point that is between -19 dB and 7 dB.

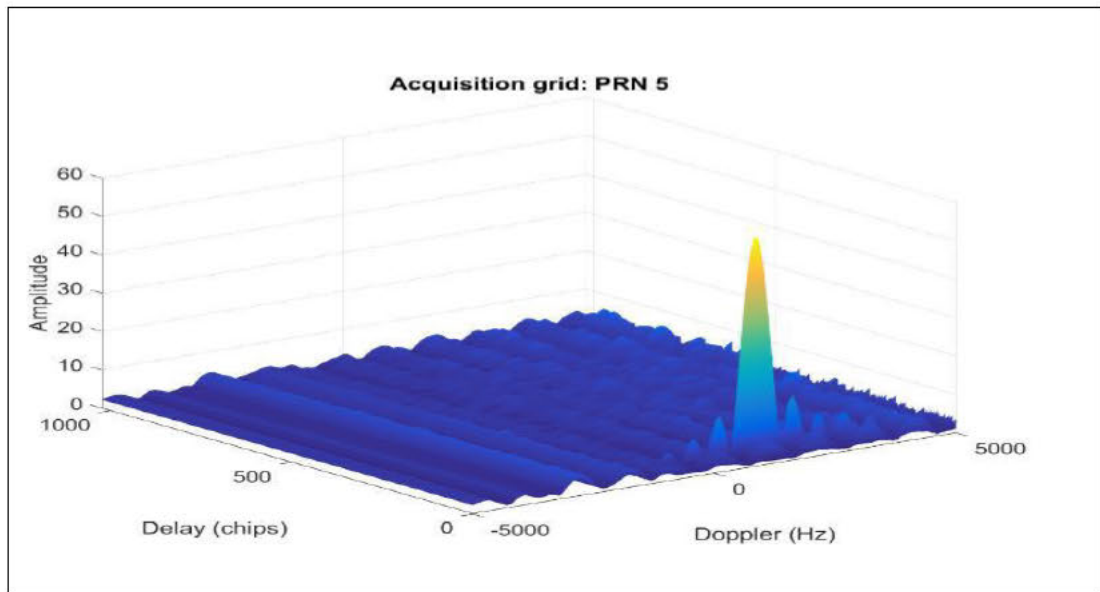


Figure 4.11: The GNSS signal acquisition grid for PRN5.

The amplitude of the incoming signal depends on the code delay and the Doppler shift frequencies. In Figure 4.12, the acquisition grid for PRN4 is shown to explain the correlation between the Doppler, code delay and the amplitude of the incoming signal for GPS constellation.

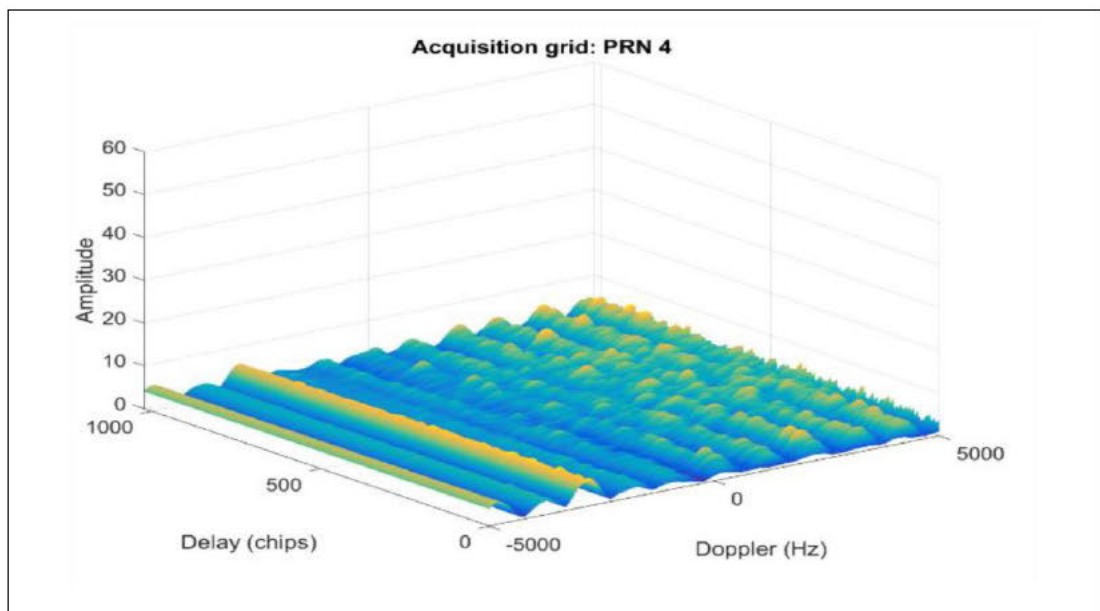


Figure 4.12: The GNSS signal acquisition for PRN4.

Figure 4.12 illustrates the GNSS acquisition grid for GPS L-1 C/A signals. In Figure 3.11 and 3.12, the GNSS acquisition is successful, and the probable

Doppler is about 1500 Hz and the code delay is 186 chips, respectively. If the resolution of the code delay is half a chip along with the Doppler frequency of 150 Hz, adhering to a code delay of 2046 and a Doppler frequency of 10000 Hz, the correlation for each PRN will be $2046 \times 10000 / 150 = 136400$ Hz. In this context, the Doppler frequency is referring to Doppler frequency residuals that describe the difference between the local carrier and received frequencies, respectively. Hence, if the GNSS receiver receives the Doppler frequency of 1000 Hz and the locally generated frequency is 3000 Hz, the difference between them is 2000 Hz, and it will give the same results as 1000 Hz and 3000 Hz, correspondingly. Numerous acquisition methodologies have been developed and embedded in other systems to accelerate the correlation process in the context of GNSS signal processing. Most of these acquisition methods use parallel searching and are based on the Fast Fourier Transform (FFT) statistical algorithms. Hence, the CSD in the context of multiconstellation (Galileo and GPS) will be implemented and described in six sequential stages.

1. 1st Step (CSD Preparation) : The GNSS signal initialisation

There are inputs parameters of the CSD that need to be defined in the preparation step and these inputs are :

- The uncertainty range of the Doppler frequencies

This is aligned to the parallel search acquisition method; the number of the Doppler frequency bins and standard algorithms secure their resolutions. Therefore, the Doppler frequency bin in this context is denoted by $f_{D,b}$ and estimated using equation (4.21).

$$f_{D,b} = \frac{f_{D_x, \max} - f_{D_x, \min}}{\frac{1}{t_{\text{coh}_x}}} = 2f_{D_x, \max} \times t_{\text{coh}_x} \quad (4.21)$$

Where the $f_{D_x, \max}$ denote the maximum value of the projected incoming Doppler frequency and $f_{D_x, \min}$ is the minimum value incoming Doppler frequency from the specific satellites (in this case is Galileo and GPS). The $\frac{1}{t_{\text{coh}_x}}$ is the coherent integration period of the signals.

In context of the multiconstellation between the Galileo and GPS, the code delay blocks are equal to Doppler frequency bins.

In the Doppler frequency, the period of single block is denoted by $t_{b, \text{single}}$ and is estimated using the following numerical algorithms

$$t_{b,single} = \frac{1}{2f_{D_x,max}} \quad (4.22)$$

The number of blocks contain the data samples and the number of samples per block is denoted by $NS_{p/b}$.

$$NS_{p/b} = t_{b,single} \times f_{sa} \quad (4.23)$$

$$\Delta f_r = \frac{1}{t_{coh_x}} \quad (4.24)$$

f_{sa} is the sampling frequency and the number of the Doppler frequency bins and their resolutions are secured. The resolution of the Doppler frequency is denoted by Δf_r .

- The GNSS coherent integration periods t_{coh_x}
The GNSS coherent period is the time-domain integration of measurements of the series pulse. Hence, it improves the signal-to-noise ratio and reduces the effort required for signal processing prior to an approximation of the signal properties. The coherent integration times use the GNSS carrier phase and are capable of predicting properties like replica carrier phase using the internal state algorithms. The sensitivity is reduced to prevent the system from detecting minor discrepancies that are insignificant. These coherently integrated systems have numerous advantages. Namely;
 - The data wipe off protect the cross-correlation: In the case of a weak signal, the receiver will wait and pick up the strong signal, which has a smaller pickup compared to the weak signal.
 - Observed GNSS receiver oscillations: The atomic clock of the GNSS receiver is linear through the coherent integration period to prevent the jitters from corrupting the correlation outcomes.
 - The supported data link is the complete processing of the GNSS signal is heavily reliant on the availability of clock data and satellite ephemeris. In wireless communications and the processing of the multiconstellation signals, there are delays that are expected for several seconds.
 - Vector tracking to protect the cross-correlation:
During the processing, the GNSS receiver can sometimes switch to a vector tracking mode that requires the inter-satellite path correlation for modern GPS and Galileo signals.

Hence, the GNSS receiver cannot lock into cross-correlation since it is not possible for cross-correlation to match the desired auto-correlation peak values.

- The multipath mitigation: This is also known as the multipath mitigation in the Doppler domain. The correlation process is capable of suppressing the multipath signal if the Doppler frequency of the multipath is not equal to the Doppler frequency of the line-of-sight Doppler frequency.

2. 2nd step: The pre-processing of the received GNSS signal

The coherent integration time and uncertainty of the Doppler frequencies are known, and then the received GNSS signal need to go through pre-processing. The received GNSS signal is complex; it must be transformed to baseband signal. This stage is reliant to the intermediate frequency and the replica complex carrier is not capable of compensating the Doppler frequency of the incoming signal.

3. 3rd Step : Generating the local spreading code

The third step is the generation and conditioning of the local spreading code, the received GNSS signal has the local codes that are generated and separated into small blocks of samples to ease the acquisition and further processing. The spreading codes for GPS and Galileo signal are presented in Table 4-1.

Table 4-1: The spreading codes of the GPS and Galileo constellations

GNSS Constellation	Signal		S_{cl}	$N_{S_{c/C}}$	S_{cP}
GPS satellites	L-1C		1023	32	1
	L-1C/A		10230	63	10
Galileo satellites	E1		4092	50	4
	E5a		10230	50	1
	E5b		10230	50	1

Table 4-1; illustrate the characteristics of the GPS and Galileo satellites, respectively. Its further shows the similarities between the frequency links of

GPS and Galileo. From Table 4-1 S_{cl} denotes the length of the spreading code, $N_{S_{c/C}}$ denotes the number of spreading code per signal component and S_{cP} is the period of the spreading code.

4. 4th step: The partial correlation of the separated signals

In the fourth step, the correlation output is evaluated and computed. The partial correlation is between the divided received signal and replica to match the length of primary code per samples. The samples of the received signal are correlated with the primary zero padded code block and the first half of the correlation is preserved.

5. 5th Step: Application of numerical algorithms (FFT)

In this step, the numerical algorithm is applied to compute the parameters of the incoming signal and replica. Once, the calculation is completed the parameters are compared to estimate the signal degradation and further utilize the capabilities of the CSD to compensate the attenuated signal. The numerical algorithms adhere to the set given for required partial correlation outputs and must correspond to the code delay.

6. 6th Step: Combining the code blocks

Previously, the replica signals were divided to code blocks to ease the computation in the GNSS receiver. In this case, the code block is re-arranged while the block of the incoming signal remain unchanged. Hence, the coherent integration period is equivalent to the period of the spreading code.

4.5. Simulation Results and analysis

In this section, the simulation results and analysis of the CSD between the Galileo and GPS modernized signals are provided. The goal of this simulation is to study the CSD in multiconstellation environment, improve the signal strength using GNSS CSD and further confirm the similarities between the Galileo and GPS. Hence, this section will begin with the comparison of the signal designs for modern signals. Based on the methodology explained in Section 4.4 above, the parallel signal acquisition of the coherent integrated data plays the crucial role in improving the signal strength through multiconstellation concept. The synthesis is proposed to compare the GPS and Galileo signals since the modernized signals have two components and the signal power can be distributed equally.

Hence, the signals for BeiDou and Galileo shares the frequency domain for current GPS L-1 C/A link as illustrated in Table 4-4.

Table 4-2: The frequency domain, data access, frequency band, bandwidth and centre frequencies for Galileo and GPS.

GNSS Constellation	Data access technique	Frequency Band	Bandwidth (MHz.)	Centre frequency (MHz.)
Galileo	CDMA	E1	24.552	1575.420
		E5a	25.575	1176.450
		E5b	25.575	1207.140
		E6	40.920	1278.750
GPS	CDMA	L-1	20.460	1575.450
		L-2	20.460	1227.600
		L-5	24.000	1176.450

Recent communication technologies allow the multiplexing of multiple signals on one channel. The popular multiple data access methodology is Frequency Division Multiple Access (FDMA), which has the channels in various frequency bands. The Code Division Multiple Access (CDMA) technology, which allows simultaneous communication over the same frequency band, has recently become popular. The goal of this research is to improve signal strength and reduce the impact of multipath by leveraging the capabilities of multiconstellation and CSD methodologies. Hence, the interest is in the GPS and Galileo similarities. Before the GPS and Galileo signals are modulated, the sinusoidal carrier modulates the CDMA signals through Binary Phase Shift Keying (BPSK) and Frequency Shift Keying (FSK). BPSK is the simplest and most commonly used sinusoidal modulation methodology.

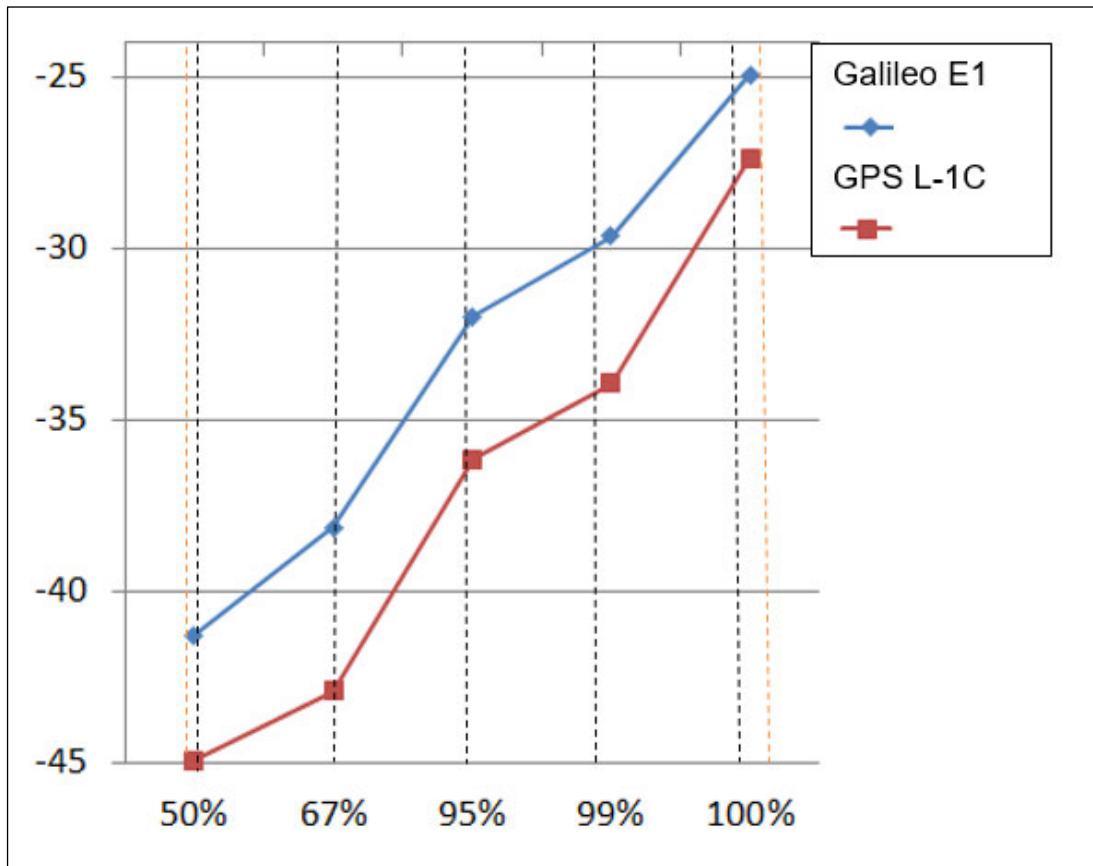


Figure 4.13: Cross correlation between Galileo E1 and GPS L-1C.

In Figure 4.13, above, the cross correlation of the GNSS signals for Galileo E1 and GPS L-1C is illustrated. In this case, both components were acquired; hence, the cross correlation was between the pilot and data for each signal link, and the codes that identify the GNSS satellite are orthogonal. The data and pilot packets during the cross correlation increase at the same rate for both signal links, as illustrated above; however, the Galileo signals have stronger augmentation systems that boost the signal strength compared to GPS. As a result, there is no visible part of E1 data and pilot cross correlation at the start. As a result, the isolation of the main peak autocorrelation is approximately similar to the isolation of the peak values between data and pilot components for both systems. Therefore, the GPS L1C and Galileo E1 have similar qualities in the peak of cross correlation, and this confirms that these systems are interoperable.

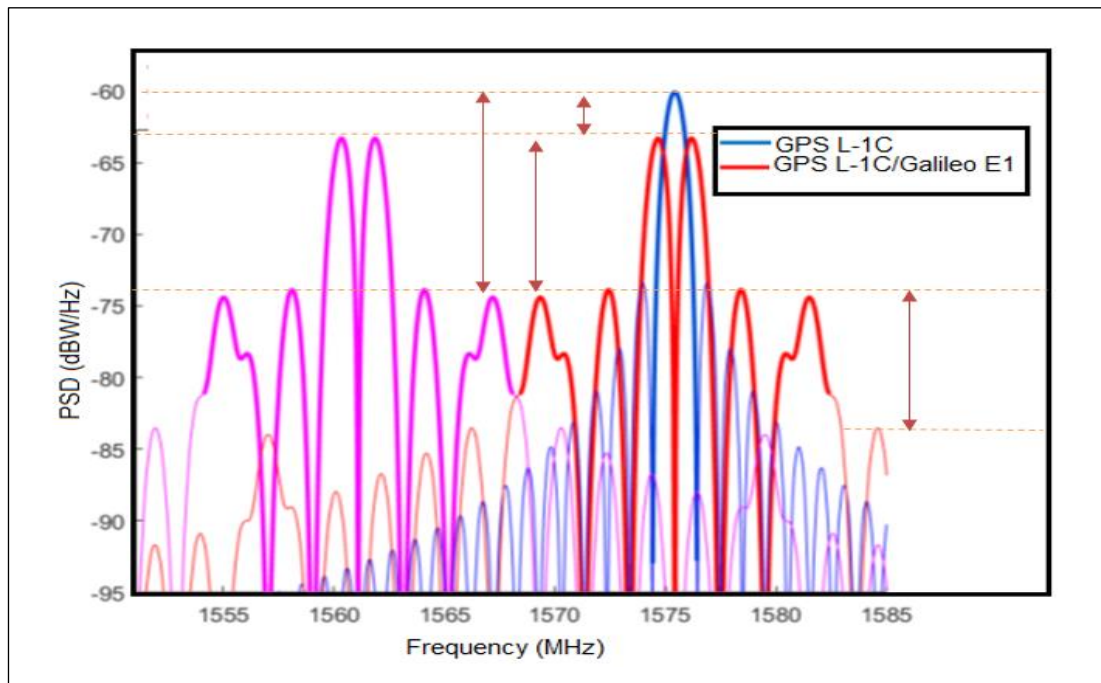


Figure 4.14 : Power Spectral Density (PSD) of signals in the L1 band.

It has been noted in Figure 4.14 that GPS L-1C and Galileo E1 share similar characteristics and qualities for acquisition and cross-correlation. Hence, here in Figure 4.14, the spectrum of the GPS L-1C is illustrated. Hence, along the center frequency, there are similarities between the BPSK for GPS and BOC for Galileo applications. Hence, these similarities further ease the operation of these systems, provided that the GNSS receiver is capable of multiconstellation signal processing. Therefore, these results prove that the GPS and Galileo are accessible and share the same frequency links. These links improve the signal strength, forward power, reverse power, and receiving signal for GPS or Galileo if there are few satellites in view for either of them, depending on the location of the GNSS receiver. The issue of poor satellite availability is highly experienced in dynamic GNSS receivers, and in such conditions, the concept of combined signal detection is helpful. In conditions where the GNSS receiver is fixed, the satellites from the GPS constellation can become faulty and compromise the signal strength, reducing the number of satellites in view. These problems badly affect the required output of the GNSS receiver, since it requires more than three satellites to calculate accurate Position Velocity and Time (PVT). In such conditions, Galileo satellites related to this application will be visible to improve the signal strength.

Both GPS L-1C and Galileo E1 are anticipated to use multiplexed binary offset carrier (MBOC) modulation for both L-1 and E1 frequency links, respectively. The MBOC is utilized for both data and pilot components. Hence, in this section, the relationship between the E1 and L1 frequency bands is analyzed comprehensively. Furthermore, the impact caused by the signal distortion and multipath for pilot and data codes along with the cross-correlation is explored to articulate the relationship between the systems. In Figure 4.13, the tracing of both data and the pilot component for Galileo E1 using MBOC is illustrated. In the poorest situations, the impact of the signal attenuation and multipath on the data and pilot codes is examined. In this case, the secondary code and data message are similar since both may not affect the outcomes of the study. Hence, the GNSS baseband signal presented in equation (4.3) is recalled and include the BOC modulation scheme.

$$S_{\tau} = \sum_{x=1}^{N_x} a_x k_x(\tau_x) + n \quad (4.25)$$

In order to introduce and accommodate the BOC modulation scheme, equation 4.26 is re-written and defined as following:

$$s(t) = \sum_{x=1}^{\infty} a[k_x] q(t - xT_c) \quad (4.26)$$

Where the

- $a[k_x]$ denote the spreading order for specific satellite in the period of N_n
- $q(t)$ denote the code spreading pictogram for the certain duration T_n
- $s(t)$ is the pseudorange signal or waveform for the period of NT_n

The $q(t)$ is subjective to the difference or sum of BOC (1,1) and BOC (6,1) spreading codes is the signal is for Channel Binary Offset Carrier CBOC (+) and CBOC (-) modulation schemes mostly used in E1. Considering the combination of E1 and L-1, the MBOC is introduced with two additional functions, the Auto Correlation Function (ACF) and Cross Correlation Function (CCF).

$$s_1(t) = \sum_{x=-\infty}^{\infty} a_1[k_x] q_1(t - xT_c) \quad (4.27)$$

$$s_2(t) = \sum_{x=-\infty}^{\infty} a_2[k_x] q_2(t - xT_c) \quad (4.27)$$

The $a_1[k_x]$ and $a_2[k_x]$ denote the spreading orders knowns as the PRN code sequences. Hence, the CCF and ACF of equation (4.27) and (4.28) is defined as following.

$$\mathcal{F}_{s_1 \& s_2}(\tau) = \frac{1}{NT_n} \int_0^{NT_n} s_1(t + \tau) s_2(t) dt \quad (4.29)$$

The equation (4.27) to (4.28), are the efforts to describe the results attached in Figure 4.14, 4.15, 4.16 and 4.17.

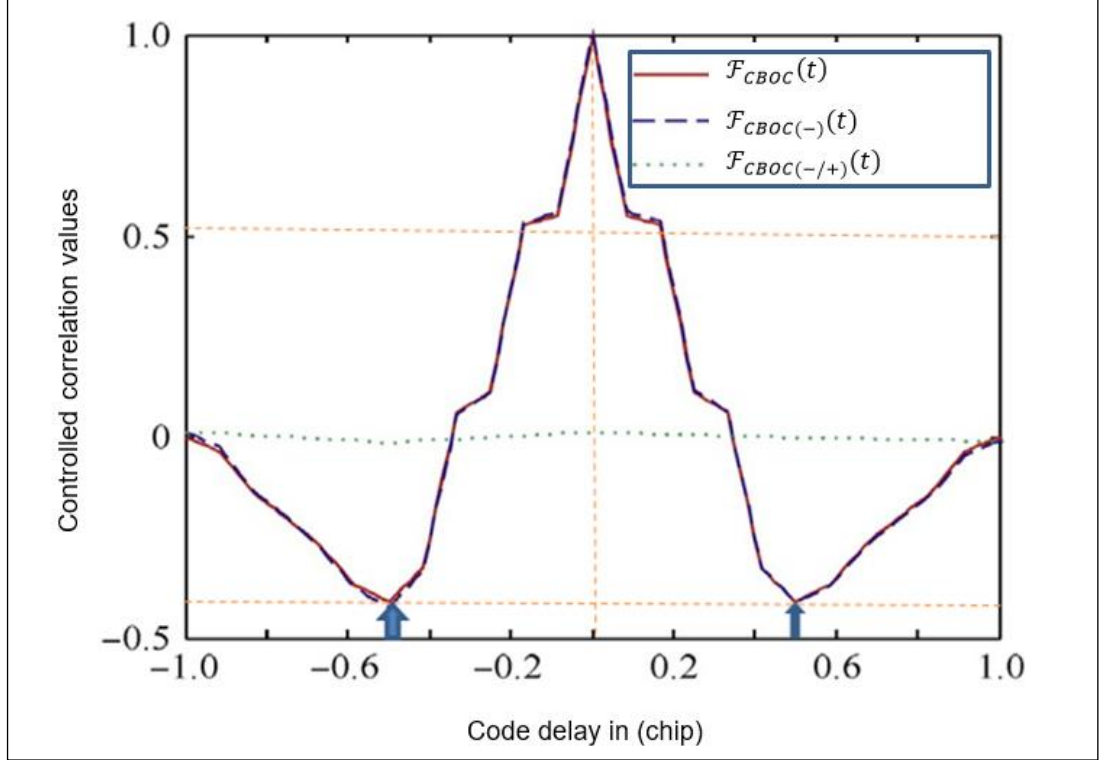


Figure 4.15 : Cross-correlation functions of CBOC signals.

If in Figure 4.15, the value of $\mathcal{F}_{s_1 \& s_2}(\tau)$ is symmetrical and $\mathcal{F}_{s_1 \& s_2}(-1)$, the central section of $\mathcal{F}_{s_1 \& s_2}(\tau)$ will be symmetrical also. This definition allows the CBOC signals to be merged with MBOC signals and further obtain the ACF and CCF for E1 PRN1 as illustrated in Figure 4.15. The ACF of the CBOC (-/+) is balanced and the CCF of CBOC (-/+) for both data and pilot components are not symmetric because of an asymmetric value of the data and pilot components. There is a strongly influence to the GNSS signal bias in the S-curve that is caused by the modulation schemes and GNSS receiver design. The simulation outcomes illustrate that, an improved data and pilot codes can expressively alleviate the impact of signal multipath, signal attenuation along the satellite path, intra-channel codes cross-correlation between E1 and L-1 and further improve the performance in terms of code tracking for MBOC (E1 and L-1) signals.

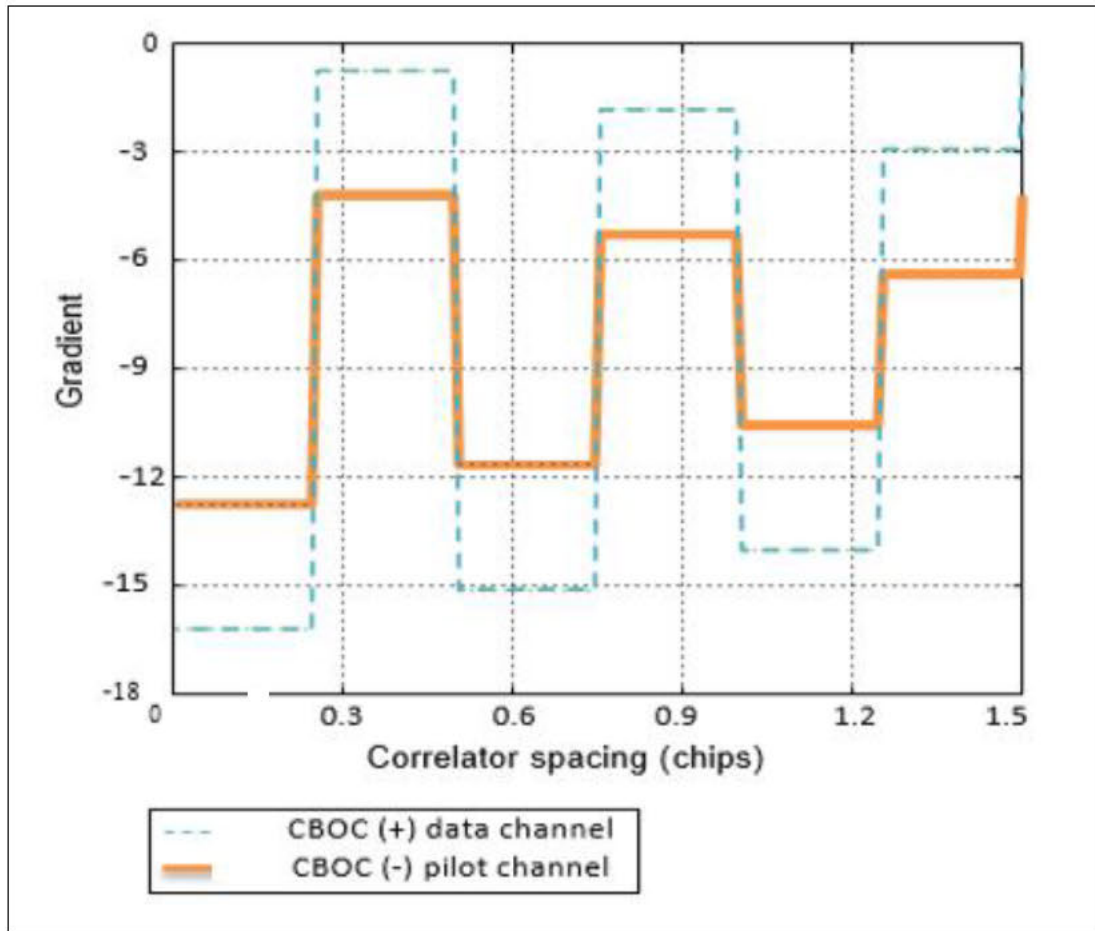


Figure 4.16: The changes of the correlator spacing for pilot and data channels : For Galileo E1 for CBOC modulation where the chip code effect is zero.

Continuing with our exploration, the pilot channel of the Galileo E1 CBOC (-) is discriminated at the point where there is a change in slope nearby zero lagging and this is illustrated in Figure 4.16. The memory code length here in Figure 4.16 is long about 12 ms instead of the standardized codes that are between 3 – 4 ms and the design of the GPS L-1 C/A data channel modulated using BPSK scheme is not capable of Galileo E1 memory codes and properties. Hence, the results of correlation is attenuated. In that case, the correlation will be not symmetrical and the impact on integration period is reduced.

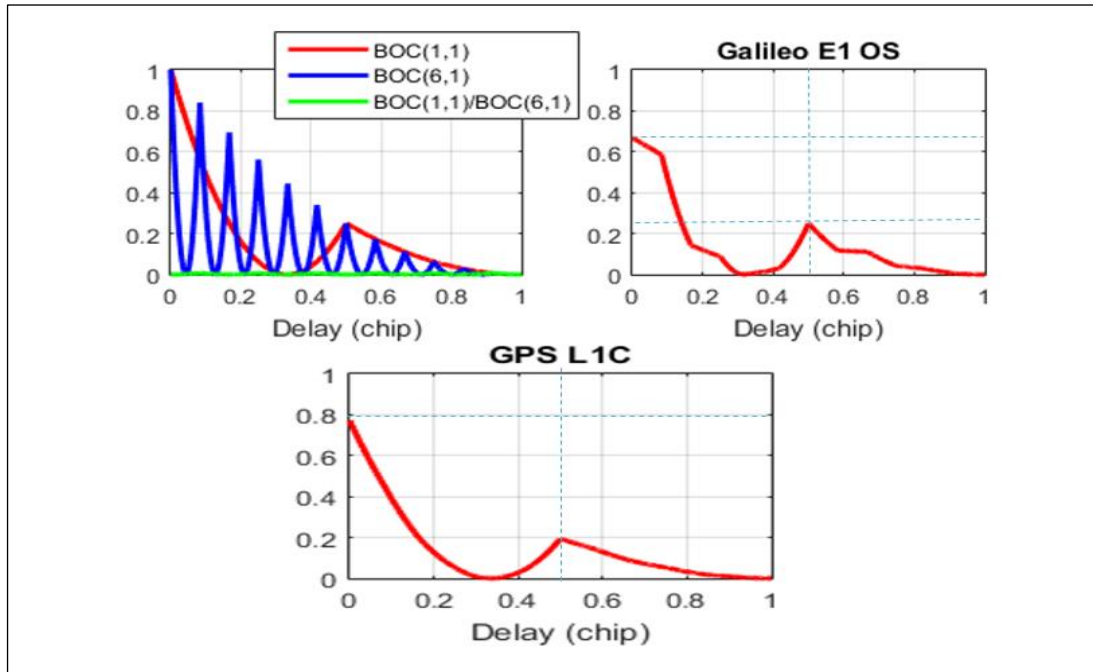


Figure 4.17 : The Data and Pilot cross-correlation.

In many cases, the pilot component is modulated using the secondary codes to provide the better results for autocorrelation. Hence, the overall chipping period is much longer because the bit of the secondary code has the similar period to the spreading code more especially for GPS signals. The data component for GPS can be further used for satellite identification. There are similarities between the GPS L1 and Galileo E1 OS signals if, both are modulated using BOC (1,1) scheme.

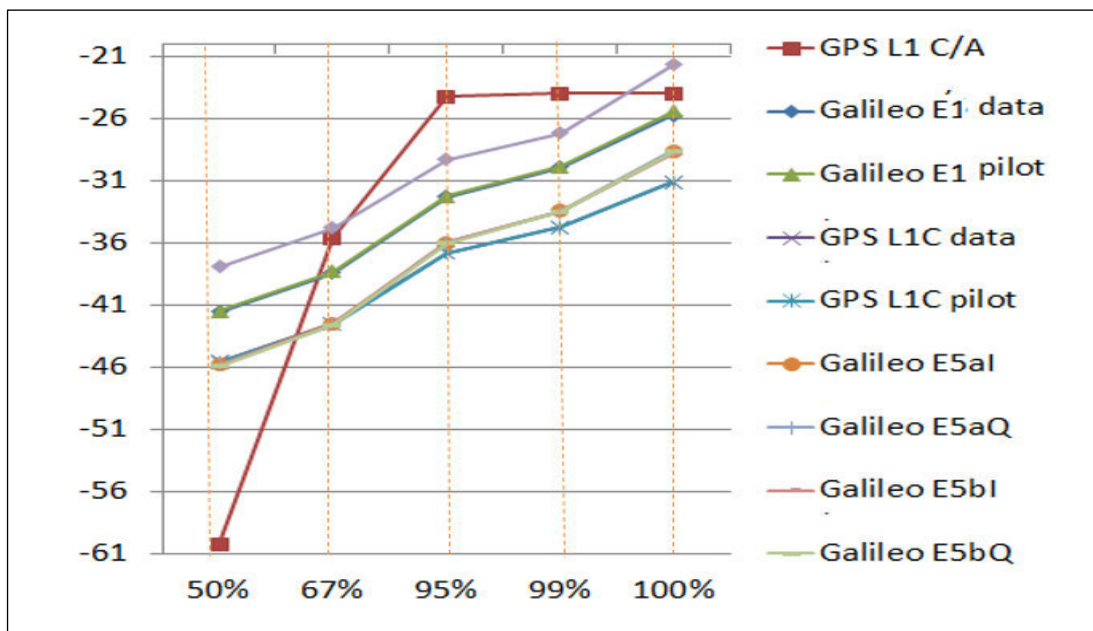


Figure 4.18 : GNSS signals spreading codes correlation.

In order to align the local signal codes and incoming signal, the longer integration period is required. The data channel CBOC (+) have higher gradient along the correlator chip, this is because this is a highly used component as illustrated in Figure 4.18.

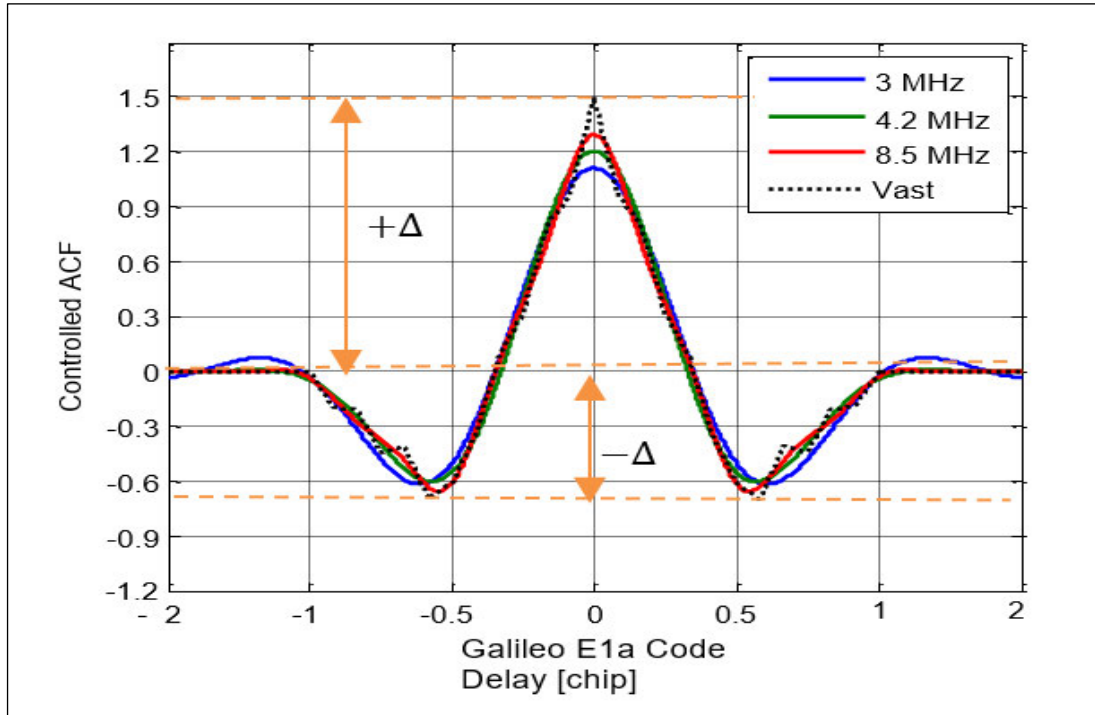


Figure 4.19: The function of GNSS auto-correlation for Galileo E1B bandwidths.

In Figure 4.19, the spreading codes for GPS and Galileo are illustrated for both phase and quadrant components. Hence, the phase modulation is utilized to pass the codes from space satellites to GNSS receivers. From Figure 4.19, it can be seen that the GPS data component is higher and stronger than the phase component because the GPS bandwidth is higher than the bandwidth of the data that is being transferred. The purpose of Figure 4.19 is to provide knowledge regarding the capabilities (the code and power spreading for signals to reach the user) for GPS and Galileo signals. Then, the phase measurements can be obtained. In Figure 4.19, the hybrid GNSS receiver capable of processing signals from all GNSS constellations—the GPS, GLONASS, BeiDou, and Galileo—and their augmentation systems was used to obtain code phase measurements for diverse radio frequency configurations.

However, the interest was only on the autocorrelation for the Galileo E1a signal. The GPS and Galileo both use a correlation spacing of 1 sample, and in Figure 4.20, the ACF of diverse frequency bandwidths and signal links is illustrated. The Galileo 5A passes through the negative change before reaching the peak of the controlled ACF, and the peak value is along the positive change. These oscillations make it possible for the GNSS receiver to recalculate the desired output without delay and integrate the data for GPS processing if required.

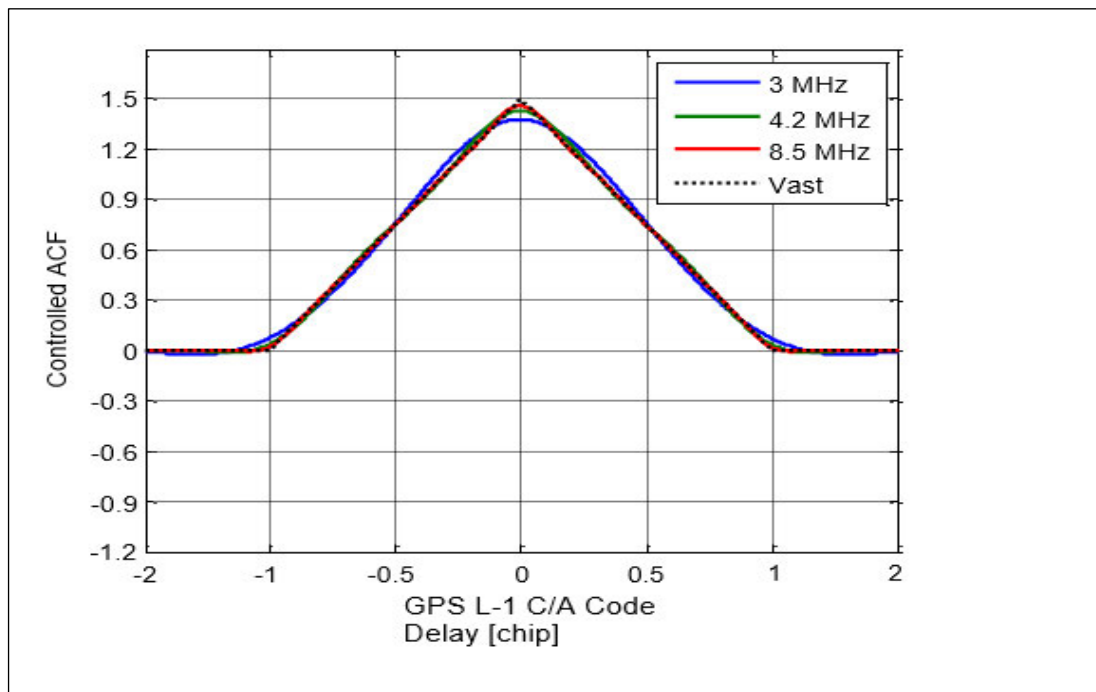


Figure 4.20: The function of GNSS auto-correlation for the GPS L1 C/A bandwidths and RF end.

From the comparison of the GPS L1 C/A in Figure 4.19 and the Galileo E1a in Figure 4.20, it can be seen that the decrease of the bandwidth causes the loss of correlation power along the peak of ACF, and this is evident for the Galileo E1a. To avoid this, the GPS is introduced with minimum loss of the correlation power, and the introduction of the GPS L-1 in this case further improves the sensitivity of the GNSS receiver to track the loops, translating to lower noise being detected and measured. On the other hand, the higher bandwidths reduce the correlation power losses and make it possible for filters to clear the peak of the ACF.

During the test, four (4) GPS satellites and four (4) Galileo satellites were visible, and Figures 4.19 and 4.20 further show that at least six (6) satellites were tracked and their signal-to-noise ratio was estimated by a GNSS receiver. The diverse bandwidth values were done, and the maximum of six satellites were tracked simultaneously. The satellite visibility was balanced in this condition, with three (3) GPS constellations and three (3) Galileo constellations. It is assumed that, if the visibility is unbalanced, there will be minor changes that are ignored. It is further noted that the estimated signal-to-noise ratio is lower for lower bandwidth filters; this is an indication that there are power losses along the signal filtration process.

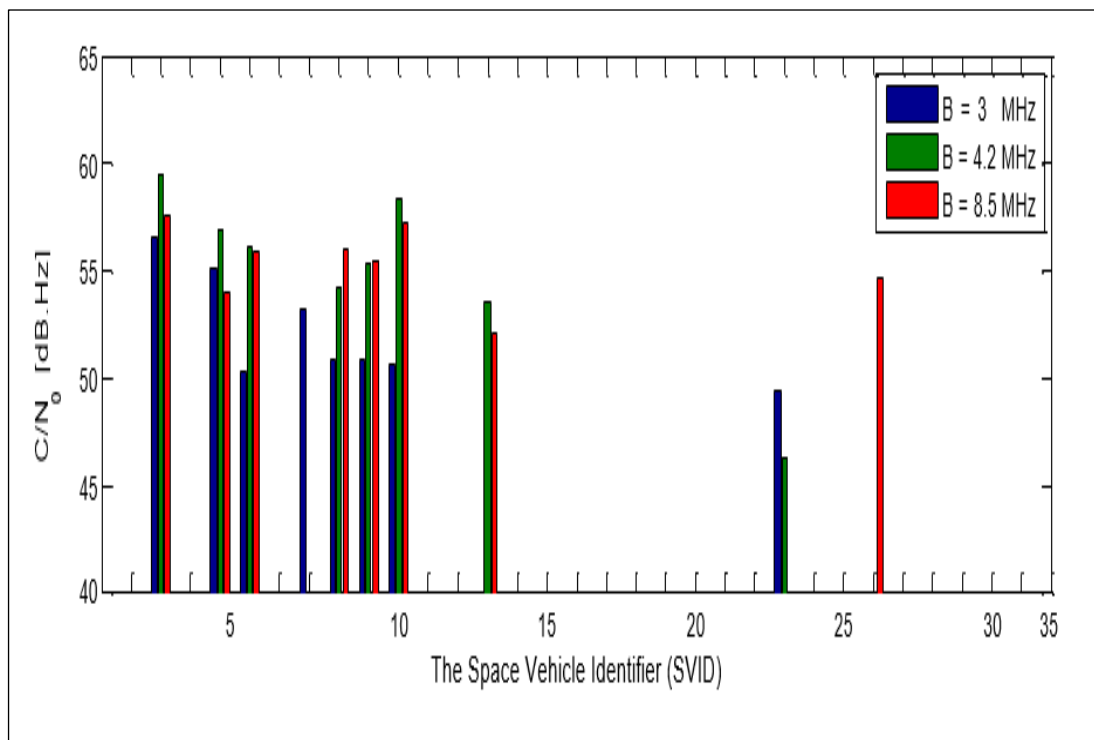


Figure 4.21: Code and satellite tracking for three bandwidths.

In Figure 4.21, the distribution of the code tracking error for GPS L1 C/A is illustrated for various bandwidths and defined as the signal to noise ratio against the space vehicle identifier. The higher bandwidths are generally associated lower code measurements. The highest value of the signal to noise ratio was recorded in the bandwidths of 4.2 MHz.

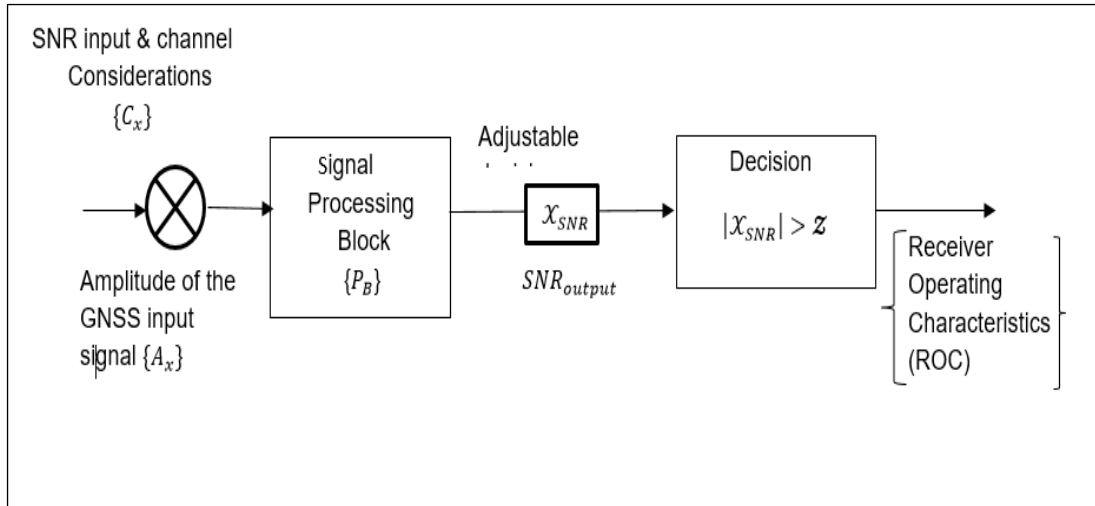


Figure 4.22: The GNSS signal acquisition block.

In the first stage of the signal processing along the GNSS receiver stages, there is acquisition block to determine if the incoming signals are from multiconstellation and further provide the approximation of the signal Doppler frequency and code delay to prepare the signals for further processing as illustrated in Figure 4.22. The acquisition block in Figure 4.22, is used to deal with GNSS signal inadequacies including the residual frequency errors and data bit transitions along the processing. The performance of the signal acquisition is determined using the SNR, the SNR in this context is known as the square difference to the mean value of the variable decision in the presence of multiconstellation signals.

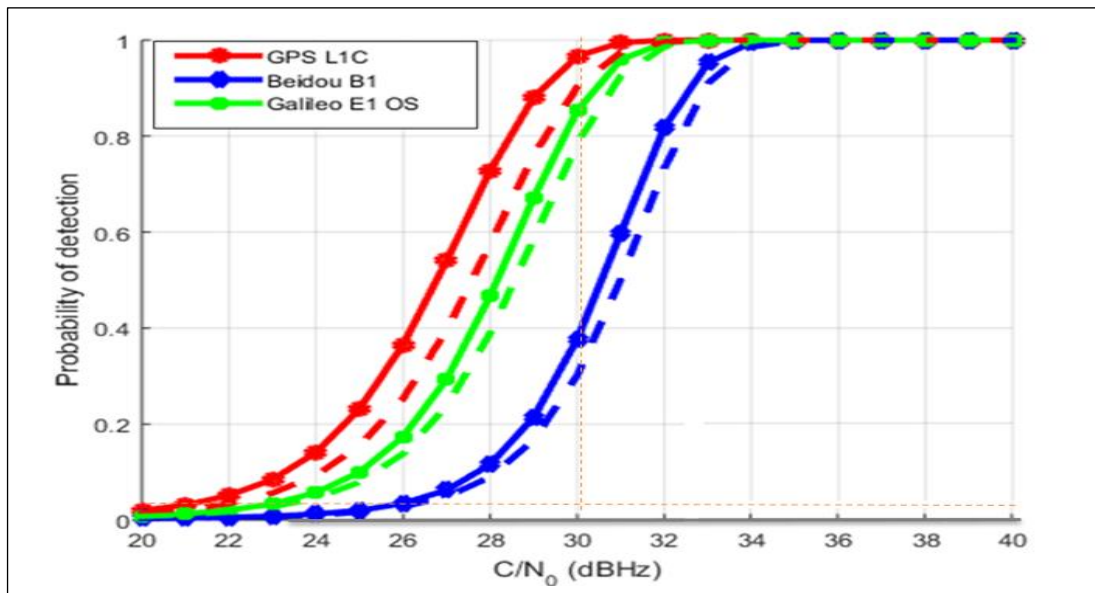


Figure 4.23: Probability of detection when acquiring both component.

The results in Figure 4.23 demonstrate the need for acquiring Galileo signals in cases of poor GPS visibility and low signal-to-noise ratio using a specific acquisition methodology that is resilient to data bit transitions. The probability of detection increases as the signal-to-noise ratio increases, similarly for both GPS and Galileo. In order to synchronize the GPS and Galileo operations, the comparison of the signal-to-noise ratio (SNR) is required to alleviate the issue of acquisition degradation due to data bit transition. In the results in Figure 4.23, it can be seen that the steadily growing probability of detection between GPS and Galileo is almost similar, which means the spectral power is also almost the same. The SNR is simply derived from the forward power from the satellite and the reverse power of the receiver. Hence, Figure 4.23 validate the objective of this research work to utilize the capabilities of Galileo signals in challenging location for single frequency GPS systems. Numerous factors can influence the SNR, but most importantly are the antenna receiver gain, the duration of the integration, and the free space loss along the satellite path. In order to remove the influence of the antenna gain, the SNR is standardized and taken into account for combined signal detection to designate the quality required from four constellations and their augmentation systems. The SNR results presented in Figure 4.23 entail the following notes:

- The SNR standardization and introduction of the CSD shows that the influence of the antenna gain and free space losses along the satellite path are minimized, hence the signal strength is improved.
- The SNR of the echoed signals Galileo signal is similar to those of the GPS
- If the coherent integration time longer about 4ms, the SNR of the Galileo is about 1 – 2 dB lower than those of GPS signals this is likely to be caused by the power transmitted and the bandwidth filter of the receiver. Hence, to improve the SNR, the coherent integration time must be longer and the improved SNR will provide the higher the signal strength at the user level. Adding 2 ms of the coherent integration can yield up to 0.4-0.8 dB improvements in the SNR.

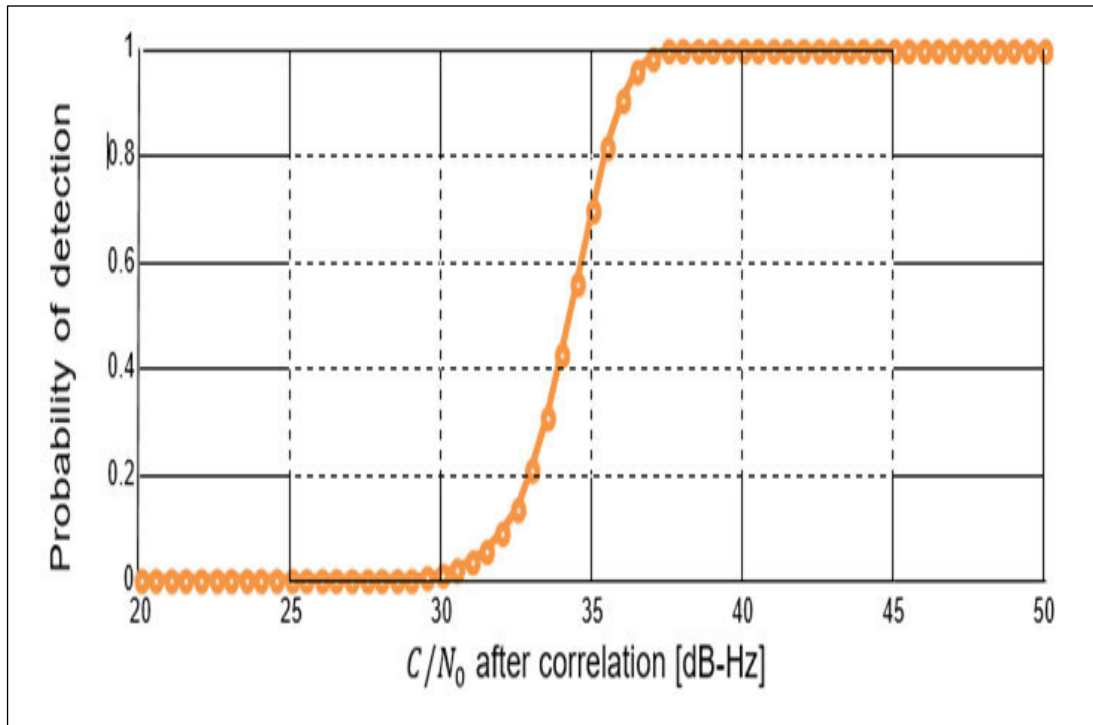


Figure 4.24: The Likelihood of detection for GPS L5 or Galileo E5a if the coherent integration period is equal to 1ms.

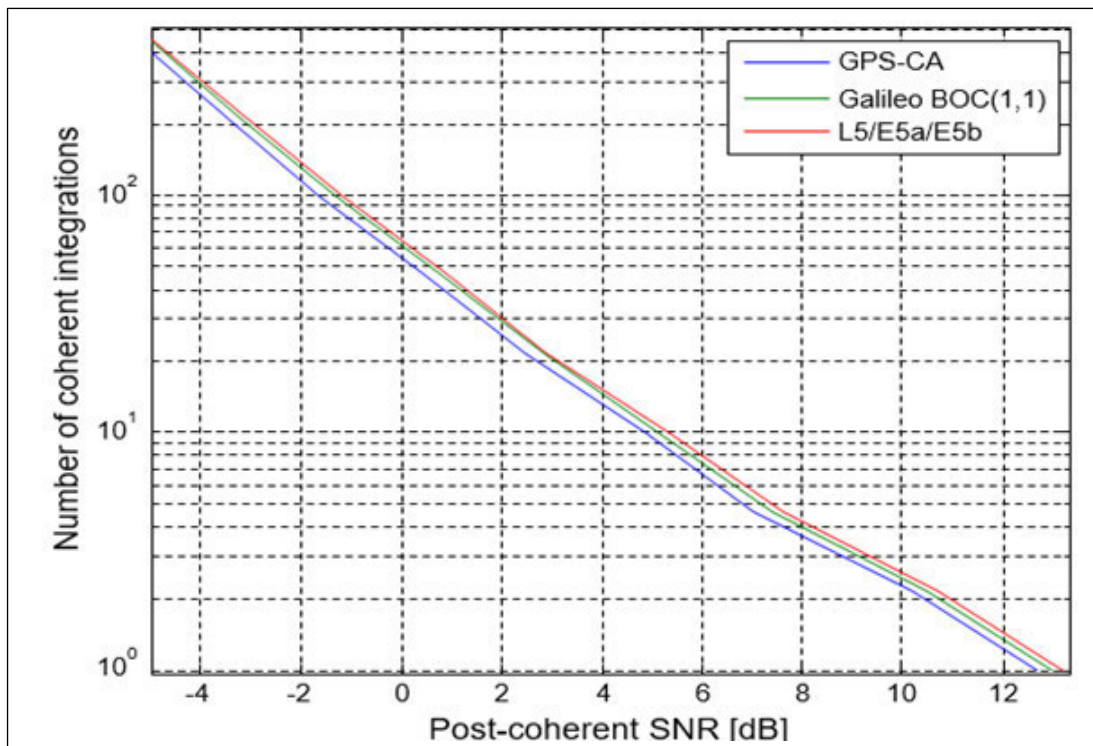


Figure 4.25: The effect of post – coherent integration on the SNR for GPS L5 and Galileo E5.

Figure 4.25 represents the number of non-coherent integrations needed to achieve the 90% probability of detection, assuming a given post-coherent SNR. Figure 4.25 shows that in order to achieve an SNR of 3-6 dB, the non-coherent integration time must be at least 1 ms and multiplied by a factor between 2 and 3. The slope in Figure 4.24, for both Galileo and GPS, is characteristically constant, and this behaviour is not influenced by the SNR outputs as illustrated in Figure 4.25. The SNR values illustrated in Figure 4.25 are compatible with the sensitivity characteristics of the GNSS receiver. The total search duration is comparable to the number of non-coherent integration periods in order to obtain the 3dB of the post-coherent SNR. This is opposite to the coherent integration; if the number of non-coherent integrations is increased, there is no negative impact in terms of the scanning area.

4.6. GNSS data bit transmission and transition for CSD technique

Galileo and GPS are two systems that were developed differently. The GPS is the old system that was further modified to meet the current demands of GNSS applications, as it is with Galileo. In this section, the performance and capabilities of GPS and Galileo are evaluated.

4.6.1. Main signal differences

The designs of the GPS and Galileo systems are different; hence, the signals emitted are different also. The key differences between the Galileo and GPS signals are the modulation schemes used, the distribution of the relative power, the content in the data message, the structure of the data message, and the rate at which the data is transmitted. However, these differences are compared and brought together in the previous sections to unify the systems.

4.6.2. The relative distribution of power

The results discussion above stated that the GPS and Galileo have a similar power level in the output of the GNSS receiver and that the power is distributed differently between the channels. The power distribution in the output of the GNSS receiver directly affects the data message since some of the incoming signal is corrupted to the extent that it cannot be recovered. In the results, it was observed that the data component has more power to alleviate the impact of the noise, attenuation, and multipath.

4.6.3. The rate of bit data transmission and transition

The GPS L-1C has a symbolic transmission rate of 100 symbols per second, and the Galileo E1a has 250 symbols per second. Hence, the transmission rate of Galileo is 2.5 times higher than GPS' transmission rate. When using the CSD presented in this research work, the final stage of signal acquisition was to certify that the signal tracking was validated once the correct cells were detected. The GPS L-1C and L-1A have the Doppler frequency that is refined by the Frequency Lock Lops (FLL), and this does not cause any notable problems. The GPS and Galileo have numerous pilot secondary codes, and the autocorrelation function for the first code needs to be determined by the signal-processing block.

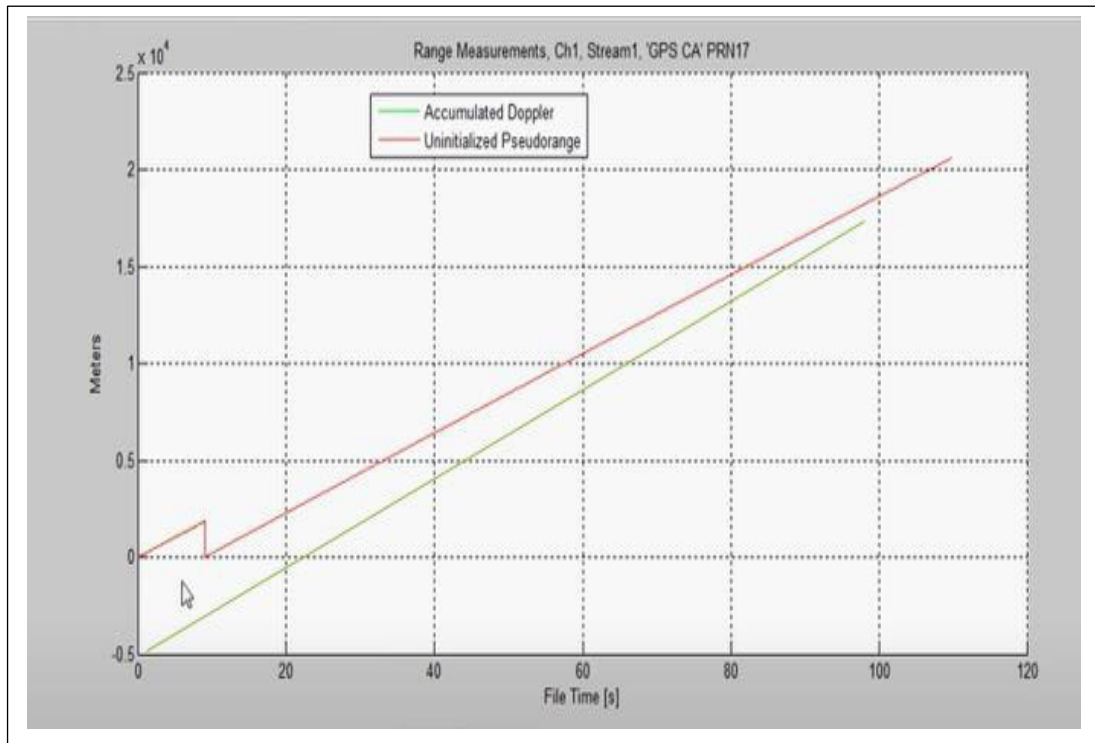


Figure 4.26 : The GPS C/A range measurements for Channel 1, PRN17 and Stream 1.

In Figure 4.26, the universal chip duration for GPS L1 CA code is illustrated. The GPS L1 CA has a chip duration that is approximately one (1) microsecond, and the GNSS receiver has a misalignment that is around one (1) microsecond. Hence, the range error will be above 200 meters and below 300 meters. The disarrangement between an accurate GNSS receiver and satellite should range between 1 and 2 percent of the code chip duration, which will result in a ranging error of 3 to 6 meters.

In Figure 4.26, there is a sudden rise of the Doppler code over two (2) minutes and an uninitiated pseudorange drop before a rapid increase over time. The GPS and Galileo are capable of negotiating with an accuracy of 3 meters. The GNSS receiver in Figure 4.26 was located in a clear view with more than four visible satellites, and the accuracy is about 2.5 meters.

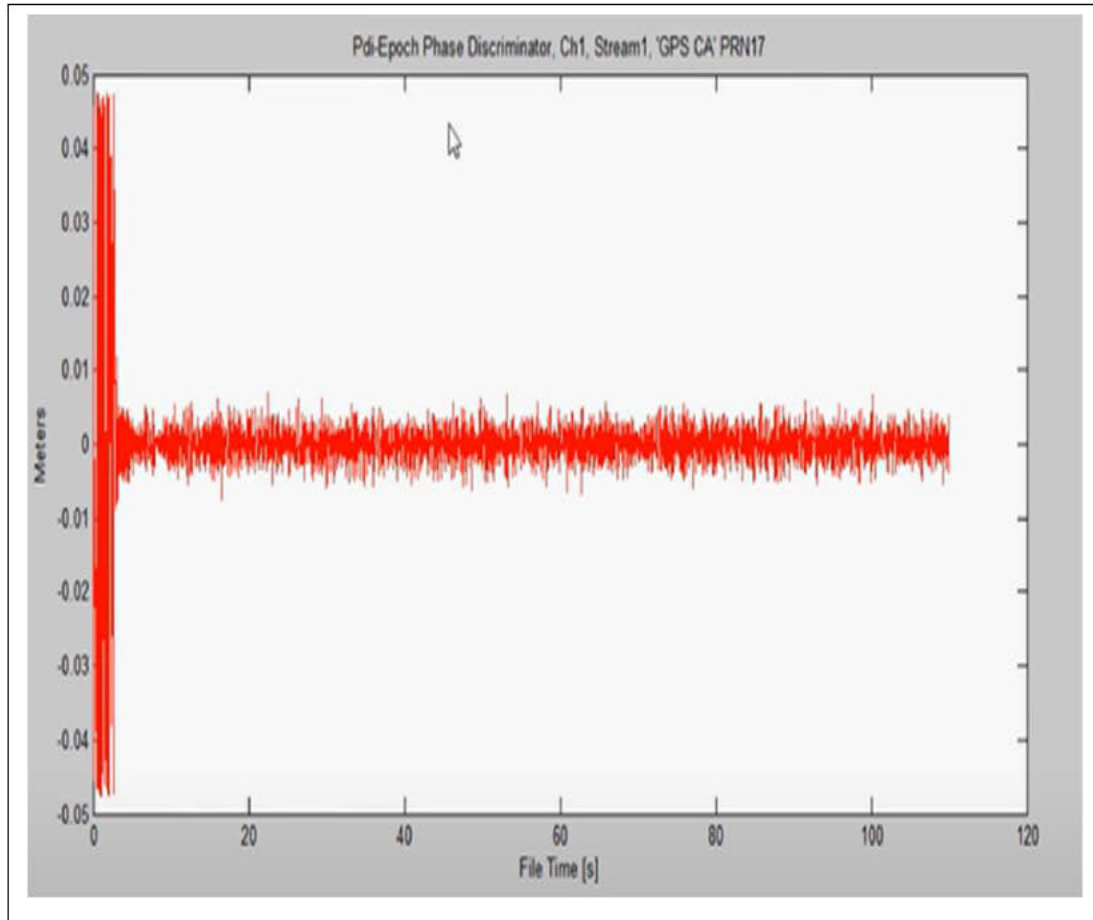


Figure 4.27 : The PDI Epoch of the phase discriminator GPS C/A.

The recent GNSS networks uses the receivers with high grade of sensitivity that are capable of operating in a low C/N_0 ratios because of the deep indoor GNSS applications that deemed as the most challenging locations. In figure 35, the classical Post Detection Integration (PDI) epoch has been illustrated for non-coherent integration. The increase of the PDI duration will increase sensitivity and accuracy in of the GNSS receiver as illustrated in Figure 4.27. The increase of PDI further increase the efficiency of the receiver by reducing the residual Doppler errors and improve the presence of the data bit. There are insignificant losses anticipated in the acquisition process.

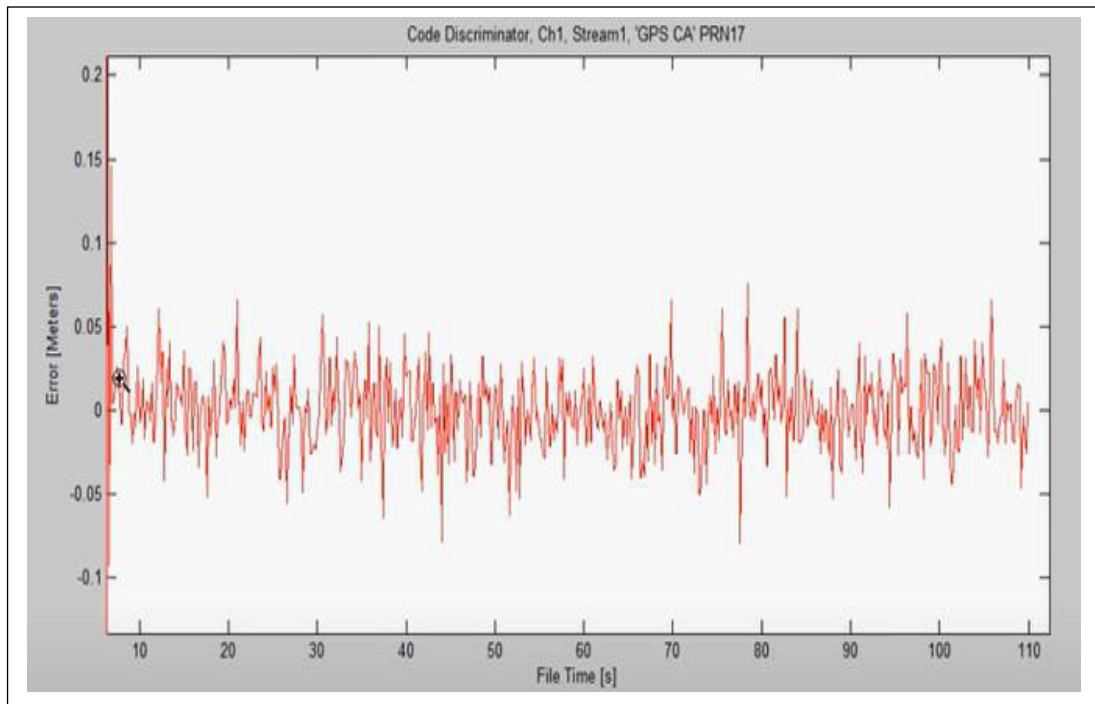


Figure 4.28: The code discriminator for GPS C/A.

The GNSS code discriminator for GPS CA is controlled by the variation of the Doppler frequency, tracking loops, code tracking, and carrier tracking if the code tracking of the GPS CA is in a clear view condition. If the requirements of navigation are met in terms of satellite visibility and without any detectable signal multipath, the carrier and code discriminator can provide clear and accurate tracking of the incoming carrier and code phase with minimal errors over processing time, as shown in Figures 4.27 and 4.28. The satellite user dynamics, clock effects, and atmosphere are likely to control the tracking loops, and the presence of the secondary signal will cause the tracking loops to track the composite instead of the direct signal.

4.6.4. Elevation angle

Regarding the elevation angle, the small elevation angle causes a longer signal propagation distance along the satellite path, and the longer distance leads to signal deterioration. Hence, the elevation angle of 5° is considered a minimum acceptable value. In Figure 4.29, three scenarios are illustrated: the variation of the signal code, phase, and SNR against the changes of the elevation angles.

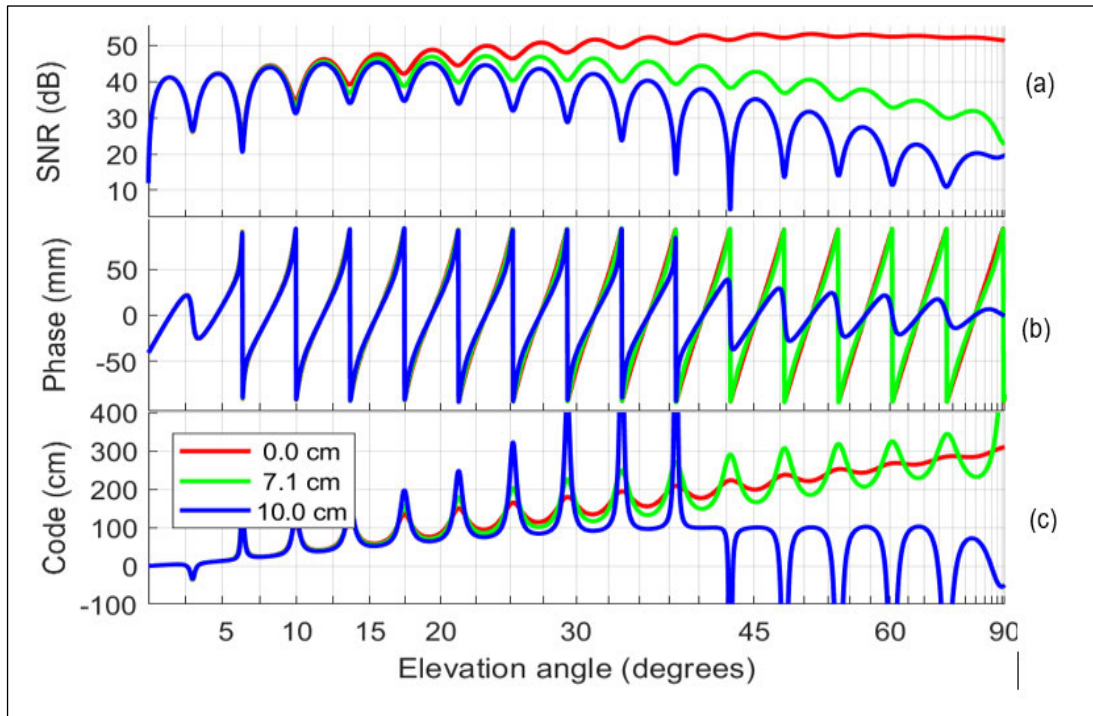


Figure 4.29 : The illustration of the code, phase and SNR against elevation angle.

The spacing scale influences the illustrations in Figure 4.29, as previously stated, the recent GNSS network employing high sensitivity and multi-frequency GNSS receivers. These receivers are capable of handling signals in challenging locations with low SNR ratios. In Figure 4.29 (a), it is shown that the higher elevation angle has the lower SNR if the scaling is 10.0 cm (blue, poor alignment between satellite and receiver), medium SNR if the scaling is about 7.1 cm (green, acceptable alignment between satellite and receiver), and high SNR if the scale is 0.0 cm (red). Hence, the ideal condition is 0.0 cm (red: ideal alignment between satellite and receiver), because the higher the SNR, the better the quality of the signal with minimum noise. Furthermore, it means there is a better elevation angle between the satellite and receiver.

4.7. Summary and conclusion

The goal of this chapter was to propose the concept of CSD. If the GNSS receiver is capable of multi-constellation signal processing, the interest is between GPS and Galileo signals. The concept of CSD has been developed and described comprehensively to express the numerical expression and further investigate performance based on GPS and Galileo signals.

It has been noted that, the signal acquisition and correlation must adhere to the design specification of the GNSS receiver. In this case, the GNSS receiver being used was capable of multi-signal processing, and the classical correlator output of the CSD was similar to the SNR values. The notable GNSS receiver losses appeared because of the following issues:

- The received signals have high incoming Doppler frequencies.
- The bit sign transition during signal acquisition
- The received Doppler frequencies between the dual frequency bins

There is a possibility of a bit transition on each of the signal components; the data and pilot for a spreading code period for both Galileo and GPS. Hence, the CSD was proposed to further reduce the inherent performance losses caused by the incoming Doppler frequencies. With this methodology, the signal losses were improved from 9 dB to 3.5 dB, and these losses were expressed in terms of probability of detection and integration time. The following chapter of this research, investigate the additional causes of the signal degradation in GNSS receivers.

CHAPTER FIVE

Investigating the signal acquisition degradation sources in GNSS receivers

Beside the multipath signal, this chapter provides an additional source that contribute towards signal attenuation in GNSS applications.

5.1. Background

The main objective of this section is to study and investigate the main causes of degradation in GNSS receivers and in terms of GNSS signal acquisition in multi-constellation environments. The properties of the GNSS signals from Galileo and GPS are studied. In practice, the selected signal acquisition grid introduces four major sources of signal acquisition and uncertainty. Hence, the existence of the data bit sign transition and the non-compensation of the Doppler code are investigated in relation to GNSS receivers capable of processing multi-constellation signals. Furthermore, an overview of the impact of the signal degradation sources is provided, and performances are computed to compare the degradation between modernized Galileo and GPS signals. The study is carried out by focusing on the probability of detection in the presence of the probable degradation sources. The purpose of this chapter is to investigate the sources of signal degradation in GNSS receivers through the modelling and analysis of the following.

- The effect of the code Doppler variations
- Rate of change of the GNSS Doppler frequency
- The analysis of the infinite bandwidth and Band-limited case
- The advanced GNSS signal carrier and code phase tracking
- The examination of the Chip Domain Observables and the output of correlation function

The results and data obtained in this chapter will be further used in chapter 6, to evaluate the performance of the CSD implemented in chapter four.

5.2. Sources of GNSS signal degradation

As mentioned above there are three sources of the signal degradation in the GNSS receiver along the signal acquisition to be studied here.

- The ambiguities along the acquisition grid cells

- The changes of the spreading code in the received signal caused by Doppler code

- The data bit and bit sign transition on the GNSS signal data component

This study quantifies the degradation of GNSS acquisition and receiver performance, particularly for newly developed GNSS constellations subject to the four degradation sources listed above. This work further investigates the loss in the probability of detection for each source of degradation that is likely to contribute towards signal multipath or attenuation. Hence, the first step is to calculate the GNSS acquisition parameters in the receiver and ensure that an adequate acquisition is reached. The average probability of detection is determined by the existence of the degradation sources. To begin with the processing and calculation, the following assumption has been made:

- The right cell in the acquisition grid is found through the thorough estimation of the code delay and Doppler frequency
- The probability detection of the referencing scenario in the absence of the degradation sources is anticipated to be $P_{PR} = 96\%$ for 28 dB-Hz signals.
- The probability of the anticipated false alarm for the signal at 28 dB-Hz is fixed to $P_{FAL} = 10^{-3}$

The sources of GNSS signal degradation are inclined to the propagation of the signal and the complete architecture of all segments involved: the space, control, and user segments. Other than the signal multipath that was the burning issue of this research work, in this chapter, the additional sources of the signal degradation are investigated and discussed. This study concentrated on the sources of degradation along the Earth's Ionosphere and Troposphere layers.

5.2.1 Ionosphere Influences

The ionosphere is the atmospheric layer that is considered to be the richest layer since it contains ionized electrons, molecules, and atoms and stretches to an approximate height of 50 km above the earth's surface, edging out to about 1000 km of space [196] .

The ionosphere is exposed to the intensive solar radiation that causes the ionization of molecules and the formation of mobile electrons. This flexible region is able to grow and shrink depending on solar circumstances. Furthermore, it can divide itself into sub-regions that are grounded in the ability of the wavelength absorption that results in the existence of the critical link of the earth-sun interface [196]. Their wavelength absorption and the electron density that is subject to change with respect to location and time, respectively describe these ionosphere sub-regions. Hence, radio wave communication at 100 MHz and below is probable in the ionosphere's atmospheric layer [196]. In this case, the space-generated waveform is transmitted to the user through the ionosphere layer. The influence of the ionosphere layer to the signal waveform is characterized by the variation of the electronics density that include the few of the follow several subdivisions.

5.2.1.1. Location-dependent variations.

In this case, the largest number of the electronics density is likely to be observed between the latitude of approximately 20° to 30° of the north and south in the geomagnetic equator [196].

5.2.1.2. Variations due to solar activity.

The variations of the solar activities result to the maximum solar radiations that are anticipated to penetrate the atmosphere and upsurge the ionization of the molecules in the ionosphere with the periodic coronal ejections [196].

5.2.1.3. Diurnal variations.

The density of the electrons changes with 24 hours (day and night cycle), due to the changes in solar radiation [196]. During the nighttime the ionization of the ionosphere decrease ominously to the minimum and the maximum ionization are reached around 2 P.M in South African time.

5.2.1.4. Seasonal variations.

The density of the electrons is subjected to the seasonal changes conforming to the diurnal vibrations. This caused by the changes in solar radiations, some seasons are hot and rainy such as summer and other are cold and snowy such as winter.

5.2.1.5. Ionosphere refraction

The bending of the radio wave from the direct geometric path between the space satellite and the ground user is caused by the refractive index of the earth, where the high elevation angle is produced compared to the direct geometric path [196].

5.2.2. Overview of Tropospheric Propagation

The serious consideration when designing the satellite communicating network must be given to the process by which the radio signal waveform propagate from the transmitting satellite to the receiving antenna and the radio paths are administrated by the relevant atmospheric area where the signal passes [197]. As the results without the aid of the atmosphere, the space satellite to ground user would have been difficult to achieve.

5.2.2.1. Tropospheric Influences

The troposphere is the atmospheric layer below the ionosphere that consists of water vapor and dry gases, respectively. The troposphere extends up to approximately 8-14 km above the earth's surface and is thought to be the denser region of the atmosphere where weather-related processes originate [197]. The tropospheric region is anticipated to contain about 80% of the atmospheric mass, where the air refractive index plays the foremost role in radio wave signal propagation. However, such influences depend upon the humidity, pressure, and temperature. Furthermore, the random and non-linear processes are caused by the radiation, absorption, convection, and diffusion of the water vapor and dry gases in the troposphere.

5.2.2.2. Tropospheric scintillation

The scintillation in the tropospheric layer is caused by the instabilities and anomalies of the refractive index in the atmosphere; this is expected in the first few kilometers from the surface of the ground [197]. The scintillation changes with the time and strongly dependent to the elevation angle, carrier frequency and the weather conditions. The L1 frequency band is likely to be affected by the scintillation.

5.2.2.3. Tropospheric path delay

The path delay in the tropospheric layer of the atmosphere is caused by the varying of the corresponding refractive index caused by the signal traverses of the densities in the atmosphere [197]. Therefore, the changes in the ionosphere as the result of the refractive index results in the signal bending and the path delay.

5.2.2.4. Tropospheric attenuation

The attenuation is mainly caused by three sources, namely rainfall, water vapour and oxygen. All these sources of signal attenuation strongly depend upon the frequencies with the larger frequency result in severe attenuation [197]. The extent of the oxygen and water vapor signal depend upon the content of the water in the atmosphere; while the rainfall caused signal, attenuation depend upon the actual amount and the duration of the rainfall.

5.2.2.5. Doppler shift

The Doppler shift is caused by the motion of the transmitter in relation to the receiver. Hence, this is called the deferential frequency between the nominal frequency of the signal and the apparent frequency [198]. The satellite based navigational services such as GPS and Glonass are likely to produce the shifted signals due to the space satellite motion in relation to the ground user.

5.2.2.6. User environment

The user-based environment effects are referring to the degradation of the signal along the communication channel due to the receiver's location, that can be either temporary or permanent.

5.2.2.7. Shadowing effects

The user environment can obstruct the signals completely and or some partially depending on the location. The shadowing effect is caused by the obstructions such as the buildings and mountains that can result to the signal blockage and attenuation [198]. The partial attenuation of the signal is anticipated to decrease the signal power and increase the level of the noise, whereas the complete blockage is likely to affect the satellite constellation geometry to the severity.

5.2.2.8. Interference and jamming

The GNSS signals are relatively feeble, due to the long distances between the space satellite and the ground receiver [199]. Hence the GNSS signal is exposed and vulnerable to the signal jamming and the interferences.

5.3. Effect of GNSS code Doppler

The Doppler code is the code frequency that is derived of the Doppler shift of the incoming signal and is denoted by $f_{c,x,D}$. The code Doppler depends on:

- The Doppler shift of the incoming signal f_{s_x}
- The central frequency for L-band of the incoming signal f_{L_x}
- The code frequency of the incoming signal or the chip rate $f_{c,R}$

Following is the definition of the spreading code chipping time.

$$\left\{ f_{c,x,D} = f_{c,R} \times \frac{f_{L_x} + f_{s_x}}{f_{L_x}} \right\} \Leftrightarrow \left\{ T_{c,x,D} = T_{c,R} \times \frac{f_{L_x}}{f_{L_x} + f_{s_x}} \right\} \quad (5.1)$$

The chip duration period is $T_{c,s} = \frac{1}{f_{c,s}}$, the local spreading code for the incoming signal is $T_{c,R}$ and the unknown value is $(T_{c,x,D})$. There are differences in code frequency that causes variations to the spreading code period. The positive code Doppler frequency reduce the duration of the spreading code $f_{c,x,D} < T_{c,s}$ whilst, the negative Doppler shift expand the duration of the spreading code $f_{s_x} > T_{c,s}$. The motion of the satellite and local oscillations causes the changes in the Doppler frequency. Hence, these conditions affect the state of the received signal. The GNSS signal emitted from the space travels through the radio propagation channels before it arrives to the GNSS receiver. However, the direct path between the satellite and receiver is not the only way for the signal to reach the antenna as the wavelength are also called the delta range measurements. The signal in equation (4.2) is anticipated to be synchronized in frequency, the carrier frequency and the Doppler shift of the received signal. Adhering to data sequence d_s , chip code c_c , the pulse that control the changes of the chip $c_T(t)$, the code in complete data bit C_d and data duration D_t , the baseband signal from the space is expressed.

$$\mathcal{M}_s(t) = a_s \left\{ \sum_{m_s=-\infty}^{\infty} d(m_s) \sum_{k_s=0}^{D_t-1} \sum_{n_s=0}^{L_t-1} c_c(k_s) c_T(t - \tau_s - k_s T_{c,s} - r T_{PRN} - m_s D_t) + w_t(t) \right\} \quad (5.2)$$

Where $c_T(t)$ denote the transmitted signal pulse that is to be filtered by precorrelation at filter and the last term $w_t(t)$ represent the thermal noise in the baseband signal. The concept of the GNSS synchronization is to estimate the carrier phase data δ_s and the τ_s time delay in the amplitude of the complex signal $a_s = a_s e^{j\delta_s}$.

The $c_T(t)$ signal pulse is filtered at precorrelation and numerically expressed in Equation (5.3) and the GNSS receiver optimum code filter output is expressed in Equation (5.4).

$$\mathcal{M}_s(t) = a_s \sum_{m_s=-\infty}^{\infty} d(m_s) \dot{g}(t - \tau_s) + w_t(t) \quad (5.3)$$

$$\mathcal{L}_{CF} = \mathcal{P}_R(-t + D_t L_t) + n_a(t) \quad (5.4)$$

The function of $n_a(t)$ denote the additive noise and the last stage of code filter is expressed as:

$$\mathcal{Q}_{CF} = a_s \sum_{m_s=-\infty}^{\infty} d(m_s) \dot{g}(t - \tau_s) * \mathcal{P}_R(-t + D_t L_t) + n_a(t) \quad (5.5)$$

Therefore, the changes of the code frequency cause changes to the spreading GNSS code period as illustrated in Figure 5.1. This is illustrated over the four (4) chip spreading code frequency and three (3) periods.

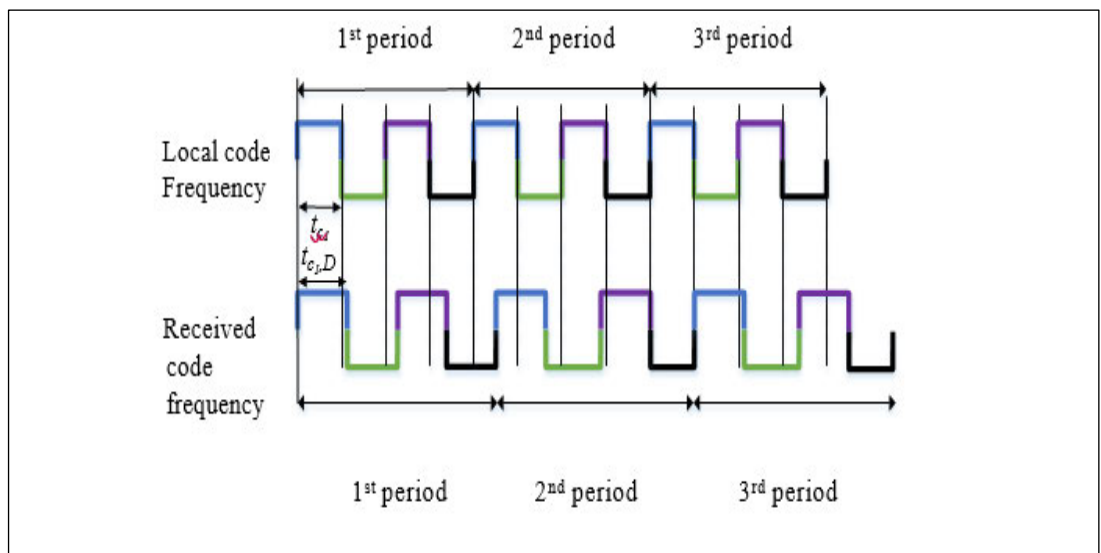


Figure 5.1: The changes of the GNSS spreading code.

The Doppler effect is neglected if the absolute value of the incoming Doppler frequency is small. The value of the incoming Doppler frequency depends upon the parameters of the incoming signal. In cases of higher Doppler conditions, the absolute impact of the code Doppler in signal acquisition is substantial. If the incoming Doppler shift frequency is approximately 10 kHz, the impact of the code Doppler shift decodes to the spreading code of the GPS L1 C/A in approximately 152 ms. The acquisition of the modernized signals is anticipated to have a large chipping rate, and the acquisition of the weak signals due to distortion and multipath might require longer chip durations. Hence, these conditions are difficult to neglect if dealing with signal acquisition. In other cases, the GNSS receiver neglects the Doppler code during the acquisition phase, and this causes degradation to the correlator output and further degrades the capabilities of the receiver. Hence, the local PRN code has the insignificant code Doppler. As a result, it is appropriate to discuss the effect of the code Doppler for GNSS signal acquisition in terms of probability detection if there is no compensation from the GNSS receiver. The effect of the code Doppler in GPS L1 C/A signal acquisition is studied comprehensively to apply the findings to the new signals of the GPS constellation. In this research work, the Doppler frequency is anticipated to be continuous over the complete analysis since the highest rate of change for the Doppler frequency of the incoming signal is slow, in the order of 1 Hz. Hence, the Doppler frequency of the received GNSS signal depends upon the central frequency L band, the oscillator quality, and the relative motion between the satellite and receiver.

5.3.1 Generalities on code Doppler effect

The changes in the code Doppler causes changes to the period of the spreading code. The period of the spreading code is illustrated in Table 5-1, and the slip of the single chip occurs for both Galileo and the New GPS constellation. However, it has been assumed that the Doppler frequency is different for different constellations and the synchronization occurs in the beginning. Hence, the shift between the local spreading code in the absence of Doppler and the received spreading code normally exceeds one chip during the correlation process.

For recently developed constellations, the slip of one chip is shorter in modernized GPS and Galileo, and the GPS L5 and Galileo E5 require a ten-fold higher chipping rate and a longer spreading period. The GPS L5 and Galileo E5 have similar frequencies and the code Doppler. Hence, this makes it possible to exploit the capabilities and advantages of the Galileo GNSS constellation. Furthermore, the frequency of the Galileo E5b link is very close to the GPS L5 and the Galileo E5.

Table 5-1 : The duration of the spreading code and the offset of the incoming doppler frequency.

GNSS Constellation	The incoming Doppler frequency offset of one chip and the number of the spreading code time)				
	2 kHz	4 kHz	6 kHz	8 kHz	10 kHz
GPS L-1C	770 77	385 38.5	257 25.7	193 19.3	154 15.4
GPS L-1 C/A	770 770	385 385	257 257	193 193	154 154
GPS L-5	58 58	29 29	20 20	15 15	12 12
Galileo E-1	770 192.5	385 96.25	257 64.25	193 48.25	154 38.5

The income Doppler frequencies are in the orders of 2 kHz up to 10 kHz and the frequency along the sampling is about 41 MHz. Hence, the data spreading code of the first slip of the Galileo E1 sample occur firstly at 4 ms that is less than the period of the spreading code.

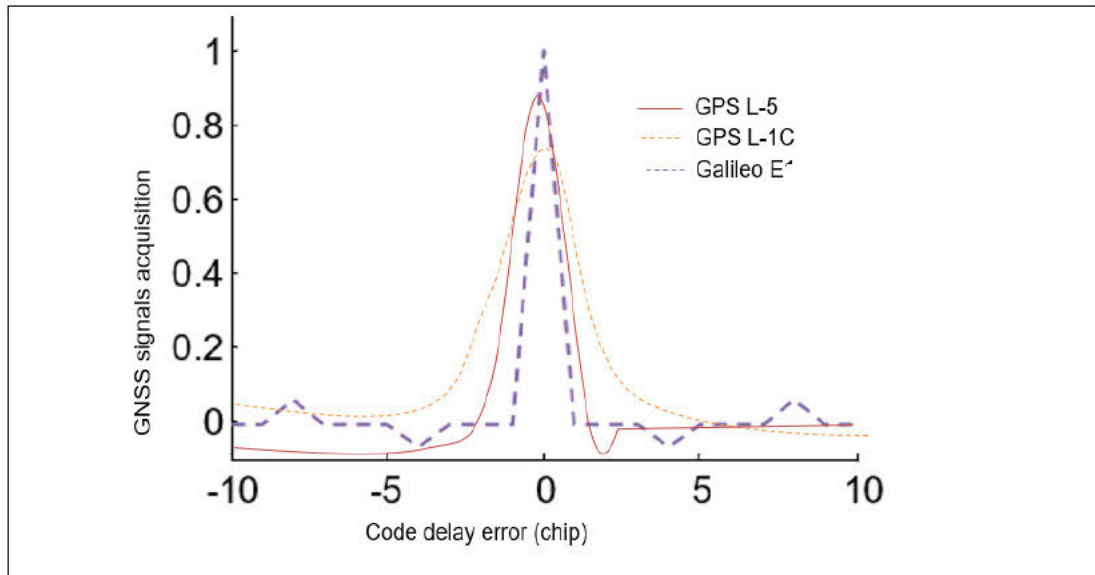


Figure 5. 2: The Signal acquisition for GPS L-5, GPS L-1C and Galileo E.

The GNSS receiver correlate the received signal and the local replica of the spreading code and the carrier code. Hence, the local spreading code is used to multiply the received GNSS signal in the front end and the new signal will be generated and integrated for the phase correlator output. The signal from the satellite to the receiver goes through the communication channels that holds numerous power levels that need to be configured correctly as shown in Table 5-2.

Table 5-2: The parameters of the GPS L-1 C/A and power levels

GPS L-1 C/A link Parameters	Power Levels
GPS user receiver power	-160.0 dB
The attenuation along the Atmosphere	-2.0 dB
GNSS receiver antenna gain	3 dB
The free space loss	-184.4 dB
The antenna gains of the satellite	13.4 dB
The antenna power of the satellite	13.4 dB
The depolarization losses	-3.4 dB

The GPS constellation has been developed to meet the requirements of the modern GNSS systems of Galileo and BeiDou. Hence, the GPS L1 C/A signal link has a frequency of 1575.42 MHz, and the detailed signal budget is illustrated in Table 5-2.

The minimum value of power for the recent GNSS signals, the Galileo E1, Galileo E5a, Galileo E5b, and the GPS L5, is articulated in Table 5-3.

Table 5-3: The received power levels for Galileo and GPS constellations

GNSS Constellation and Signal links			Received power levels
Galileo Constellation	G-E1	P	-130 dB
		D	-130 dB
	G-E5a	I	-128 dB
		Q	-128 dB
	G-E5b	I	-128 dB
		Q	-128 dB
Modernized GPS Constellation	GPS L-5	I	-127 dB
		Q	-127 dB

The Galileo and GPS constellations' frequency links are similar to each other, and these systems are interoperable with each other. Hence, the goal of this research is to improve GNSS and GPS operations by using the capabilities of the Galileo frequency links that are related to GPS. In areas where there are less than three GPS satellites in view, the Galileo satellite will be used as a third satellite to complete the requirements of trilateration. The relation between the power levels of the received signal is illustrated in table 5-3. Some environments make it difficult to handle GNSS signals, mostly for indoor applications. In these locations, the GNSS signals are extremely attenuated, and the receiving power is likely to drop to about -165 dBm because of the hard obstacles along the satellite and receiver communication path. The parameters and the physical geometry of the GNSS antenna play a crucial role in these cases.

The GNSS receiver can drop the receiving signal to about -175 dBm if it is unable to compensate for such losses. Hence, the design of the GNSS receiver is crucial to compensating losses in harsh conditions because the signal processing must be proportional to the power levels of the received signals.

5.3.2. Rate of change of the Doppler frequency

The Doppler effect was demonstrated in [2] by the comparative velocity that exists between the GNSS receiver and the satellite constellation and varies over time. Hence, to obtain the absolute value of the rate of change of the Doppler frequency, the maximum rate or average rate of change is estimated. The immobile GNSS receiver for the L-1 frequency link has the following rate of change for the Doppler frequency: the average rate of change is approximately 0.60 Hz/s and the maximum value of change is about 0.950 Hz/s, respectively. However, these values are strongly influenced by the latitude of the GNSS receiver, and in reality, the rate at which Doppler changes is not constant over the period. Hence, if the user is mobile, the average and maximum values can be very high. The mobile receiver that is moving towards the satellite direction with a gravitational acceleration of 10 is likely to cause a Doppler change of approximately 52 Hz/s. Furthermore, the type of orbit contributes towards the carrier Doppler shift despite the fact that the acceleration of the GNSS receiver is the dominant factor in terms of Doppler frequency changes. The GPS L-1 C/A signal link is capable of reaching up to 65 Hz/s for the GNSS receiver on low orbit, up to 15 Hz/s for medium orbit, and 6 Hz/s for geostationary orbit in space. There are requirements to get the Doppler observables for all types of GNSS receivers and the Doppler shift from the carrier phase for wideband frequency reaction to accommodate all dynamics in a GNSS network. The short group delay is also required to obtain the Doppler changes immediately. The summary of the sources for GNSS frequency offset are shown in Table 5-4.

Table 5-4: The sources of the frequency offset

Sources of GNSS frequency offset	Values [Hz]
Uncompensated GNSS user	± 195
The deviation of the oscillation	± 450
The motion of the GNSS satellite	± 4890
Aggregate	± 5535

The GPS constellation has satellites that are orbiting around the Earth at speeds that range from 3800 m/s to 3874 m/s. As a result, the GPS satellite's movement produces the maximum relative speed or maximum Doppler velocity of about 930 m/s to the static GNSS receiver on the ground. The relative maximum Doppler velocity between the Galileo satellites and a static multi-signal receiver is about 790 m/s. It must be noted that the motion of the satellite causes code Doppler and carrier Doppler changes between the satellite and receiver. The GPS L1C and L1 have a small Doppler frequency shift of about 1.023 MHz. The GPS L-1 C/A is 1540 times lower than, the carrier frequency. Furthermore, the latitude of the satellites influences the changes of the Doppler Effect, and the maximum values of the code Doppler and carrier Doppler for Galileo and GPS are shown in the table.

Table 5-5: The code and carrier Doppler for GPS and Galileo satellites

GNSS Signals		Code Doppler [kHz]	Carrier Doppler [kHz]
Galileo Signal	E1	2.69	4.15
	E5a	26.9	3.10
	E5b	26.9	3.18
GPS	GPS L-1	3.17	4.88
	GPS L-5	31.7	3.64

There are two types of GNSS receivers, the dynamic and static receiver. In case of the static receiver, they have the maximum shift of ± 5 KHz Doppler frequency.

The values in Table 5-5 are used by most designers and adequate for use in slow moving objects. In case of the fast-moving object, the Doppler shift is assumed to be above ± 10 kHz. These values can be influenced by the user specification.

5.4. The Numerical modelling of the signal degradation sources and distorted correlation function

The performance of the signal acquisition considering the sources of the frequency offset presented in Table 5-5 shows that the aggregate is up to 5535 Hz, and this is about 96% of the probability of detection for a signal power of around 28 dB. To calculate the probability of detection for 28 dB Hz signal levels, the Doppler frequency and code delay are estimated and accommodated along the frequency offset sources. It must be noted that the degradation along the signal acquisition line is inherent to the serial search acquisition method. In serial search methodology, the number of cells and the estimation of the residual errors determine the acquisition grid and cell width. In this section, the mathematical modeling and analysis of the signal degradation sources are provided. The approach to modeling the change of the spreading code adheres to the parameters of the received spreading code.

The received GNSS signal in the absence of the code Doppler Effect

$$M_{k,NDE} = C_k(t) \quad (5.6)$$

The received GNSS signal in the presence of the code Doppler effect

$$M_{k,DE} = C_k \left(\left(\frac{f_{c_{x,D}}}{f_c} + 1 \right) t \right) \quad (5.7)$$

To carry out this research work, an alternative methodology is proposed and the spreading codes are assumed to be in a rectangular to express the effect of the code Doppler in the received GNSS signal. The PRN code and Z_k chip of the GNSS signal without the code Doppler Effect is modelled as:

$$M_{k,No\ DCE} = \sum_{Z_k=1}^{N_{c,k}} C_k(Z) x \left(\frac{T}{T_{c,s}} - Z \right) \quad (5.8)$$

$$M_{k,DCE} = \sum_{Z_k=1}^{N_{c,k}} C_k(Z) x \left(\frac{T}{T_{c_{x,D}}} - Z \right) \quad (5.9)$$

The investigation of the GNSS signal degradation in the acquisition process is carried out between two constellations, GPS and Galileo. Hence, Tables 5-5 illustrate the similarities between the GPS and Galileo E5 in terms of time after the occurrence of a slip for one chip. It is a fact that the code Doppler causes the changes in the spreading code duration. Hence, the GPS L-5 C/A and Galileo E5a have the shorter pre-slip period in one chip, and the GPS L-1 and E1 signals have the higher time before the slip in one chip. The chipping frequency of GPS L-1 and E1 is up to 10 times higher than the E5 and L-5 frequencies. Hence, the signal acquisition of the L-1 and E1 frequency links will have rapid changes in the slip in the chips. As a result, the chipping rate is defined in equation (5.10), and the code Doppler effect reparation for in-phase and quadrature channels is defined in equation (5.10) and equation (5.11), respectively.

$$f_{cR} = f_x \left(\frac{f_D}{f_c} + 1 \right) = f_x + f_{sx} \quad (5.10)$$

Where the:

- f_x denotes the chipping rate in the absence of Doppler
- f_D is the Doppler frequency that is affecting the GNSS incoming signal
- f_c is the carrier frequency without Doppler effect in the signal

The in phase channel:

$$I_{CDC}(t_c, \tau_d, f_{dm}) = \dot{C}_{CDC} \left([t_c - \tau_d] \left[\frac{f_{dm}}{f_c} + 1 \right] \right) \cos (2\pi[f_{IN-F} - f_{dm}] t_c) \quad (5.11)$$

The quadrate channel:

$$Q_{CDC}(t_c, \tau_d, f_{dm}) = \dot{C}_{CDC} \left([t_c - \tau_d] \left[\frac{f_{dm}}{f_c} + 1 \right] \right) \text{sine} (2\pi[f_{IN-F} - f_{dm}] t_c) \quad (5.12)$$

where the:

- τ_d denotes the probable code delay
- f_{dm} denotes the probable Doppler shift

From equation (5.11) and equation (5.12), $d=1$ and $m=1$ whereas, the N_τ is the estimated number of the code delays based on the Doppler compensation methodology. Hence, the point of the locally generated code samples are at the same point with the code of the incoming signal.

The methodology of the Doppler code reparation is highly used if the issue of weak signal and higher dynamics is anticipated.

Table 5-6: The offset values for GPS and Galileo over single chip.

GNSS satellites		The offset values of one chip [ms]				
		2 kHz	4 kHz	6 kHz	8 kHz	10 kHz
Galileo Signal	E1	771	386	258	195	155
GPS Signal	L-5	59	30	21	16	15
	L-1C/A	771	386	258	195	155

It's must be noted that, the code Doppler effect is insignificant for all small integration durations. Hence, the integration period of the code shift for one signal sample is about 100 ms where the Doppler frequency is about 4.6 kHz with the sampling frequency of 4 MHz and above.

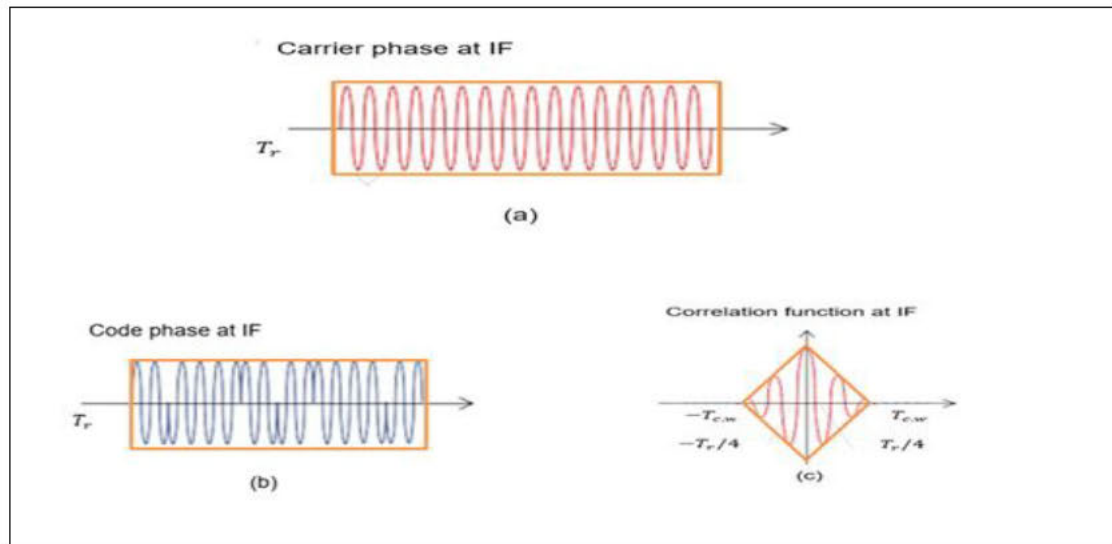


Figure 5.3 : The illustration of the carrier phase at IF (a), the code phase at IF (B) and the correlation function at IF (c).

The baseband GNSS signal have the code modulated into IF signal. In case of baseband code being modulated into IF, the spectrum will not split in the centre just like BOC signals. The correlation of the IF is illustrated in Figure 5.3 (a) and it is not similar to those of the BOC signals. These condition is called Sinusoidal Offset Carrier (SOC) and the correlation function form the envelop shape as shown in Figure 5.3 (c).

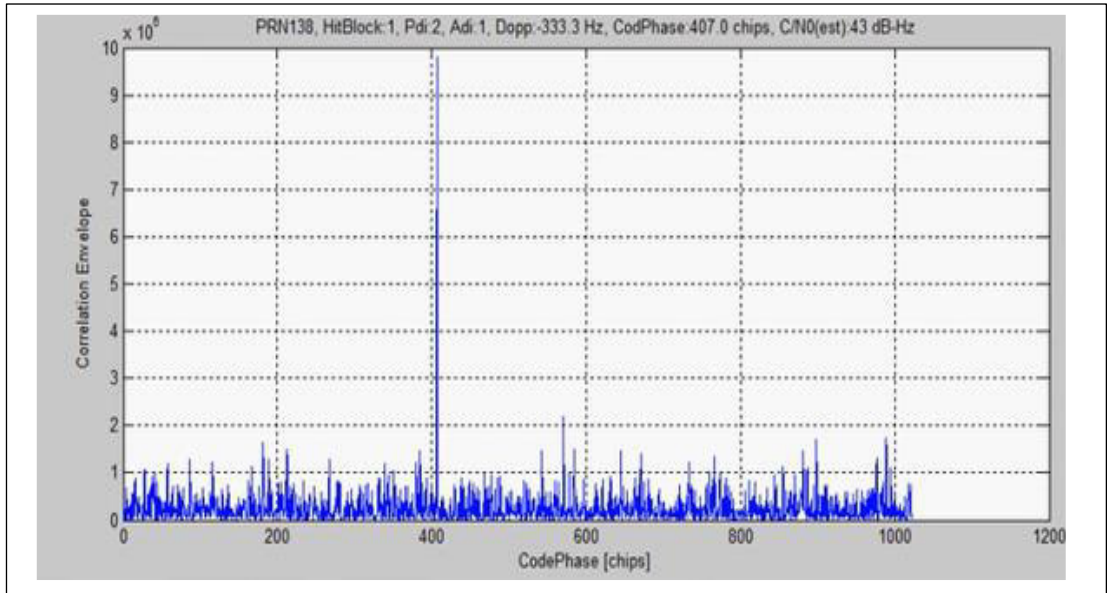


Figure 5.4: The Doppler, Code phase and C/N_0 for correlation envelope.

The signal correlation strongly depends on the spreading code, as it was stated in previous chapters. The spreading code that is popular in GNSS is selected according to the properties of auto-correlation and cross-correlation. Hence, the spreading code is selected to ensure the lowest values of both cross-correlation and auto-correlation, not unless the system is designed and configured to correspond to the chip code of the incoming signal that is aligned with the replica signal.

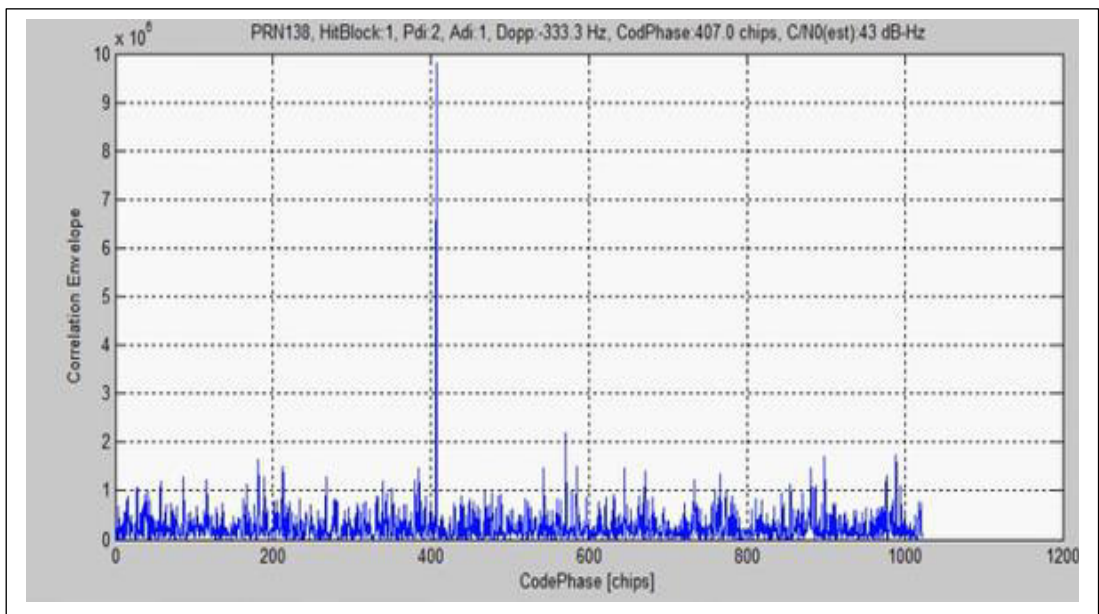


Figure 5.5: Changes of the Doppler, Code phase and C/N_0 for correlation envelope.

In Figure 5.4, the correlation envelope against the code phase is illustrated above. The maximum values of the correlation envelope are reached if the code phase is between 350 and 400 chips. As shown in the figure above, if the code phase is 400 chips, the Doppler shift is -333.3 Hz and the frequency is between 40 dB Hz and 44 dB Hz. In Figure 5.5 below the code phase is at about 2900 chips, the Doppler shift at -666.8 Hz and the code phase is at 45 dB-Hz. This means, as the correlation proceeds, the Doppler shift will become smaller and the carrier-to-noise ratio will increase. Hence, to overcome such issues, more especially the increase in the carrier-to-noise ratio, the duration of the correlation must be kept at minimum values.

5.4.1. The infinite GNSS bandwidth and limited bandwidth

Before the analysis of the limited and infinite bandwidths, it is very important to evaluate the behavior of the thermal noise in the received GNSS signal. There are two options for evaluating the thermal noise behavior: dynamic and receiver response modeling. Both are evaluated by verifying the signal transfer function of the receiver multi-tracking loop. Hence, the response of the tracking loop for multi signal GNSS receiver in presence of the additive thermal noise explored.

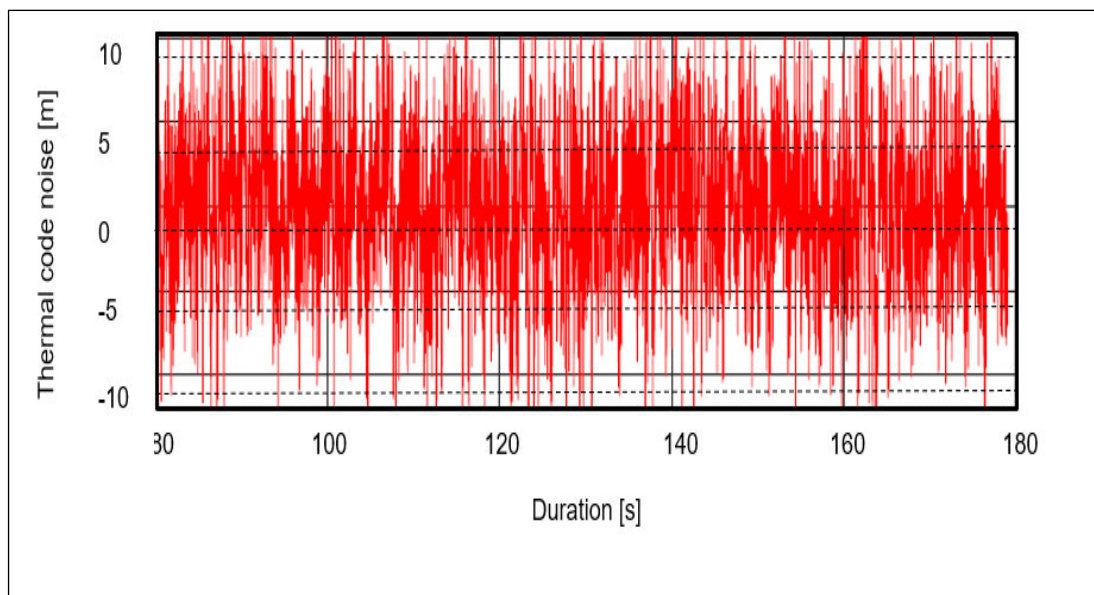


Figure 5.6: The illustration of the thermal code noise for code error tracking. Figure 5.6 illustrates the thermal code noise, also referred to as the code tracking error.

This is the signal transfer function of the $C/N_0 = 45$ dB Hz, the 5 Hz loop filter bandwidth, and the 180-second duration. The code and phase thermal noise have different auto-correlation peak values. Proceeding to the infinite bandwidth, this is used to evaluate the behavior of the thermal noise in the chips that are in a rectangular shape. The GPS L-1 C/A code is used in this case, the carrier frequency is 1.575 GHz, and the chip length ranges between 280 and 300 meters. The numerical expression to estimate the thermal code noise of the infinite bandwidth with the correlator spacing is illustrated in equation (5.13). This is the non-coherent integration of an early-late loop.

$$B_{\infty}^{code} = \frac{\tau_d x B_{LF}}{2(C/N_0)} \left(1 + \frac{2}{T_{c,s}(C/N_0)(2-d_c)} \right) \quad (5.13)$$

The thermal phase noise for the infinite bandwidth is:

$$B_{\infty}^{phase} = \frac{\tau_d x B_{LF}}{2(C/N_0)} \left(1 + \frac{2}{T_{c,s}(C/N_0)(2-d_c)} \right) \quad (5.14)$$

The limited bandwidth is used for rectangular signals for GPS L-5, Galileo E5a, and E5a. These GNSS signals have a high chipping rate, and the front-end GNSS receiver is likely to be exposed in the main lobe of the received signal and power spectrum.

$$B_{\ell} = \left((2\pi)^2 x (C/N_0) \frac{B_{LF} \int_{-c}^c \text{sinc}^2(\pi f_{sx}) \text{sinc}^2(\pi f_{sx} d_c) d_c f_{sx}}{\left(\int_{-c}^c \text{sinc}^2(\pi f_{sx}) \text{sinc}^2(\pi f_{sx} d_c) d_c f_{sx} \right)^2} \right) \quad (5.15)$$

From equation (5.15), c is the band-limiting parameter for limited bandwidth. The relationship in terms of limited bandwidth for Galileo E5a, E5b, and GPS L-5 makes it possible for these two systems to be integrated to minimize the signal multipath and power losses along the satellite path.

5.4.2. The advanced GNSS signal carrier and code phase tracking

This section analyzes the carrier and code phase tracking of the multi-signal GNSS receiver while using adaptive gain control. The (AGC) Automatic Gain Control is a crucial component of the GNSS receiver because it lowers the power losses in the incoming signal. The AGC is here explained in terms of time and frequency domains, building up to the code and carrier tracking. The time domain makes use of the locally generated replica carrier phase to track the carrier of the received signal, the frequency domain, track the noise of the received carrier, and further filter the additive thermal noise of the carrier phase.

Hence, the precise carrier replica is obtained, and the noise entering the bandwidth is controlled. The GNSS receiver used is exposed to multiple signals. To control the loop gain based on the different PRN codes and signal strengths, the inertia element and the loop gain controlling factor G_c are introduced.

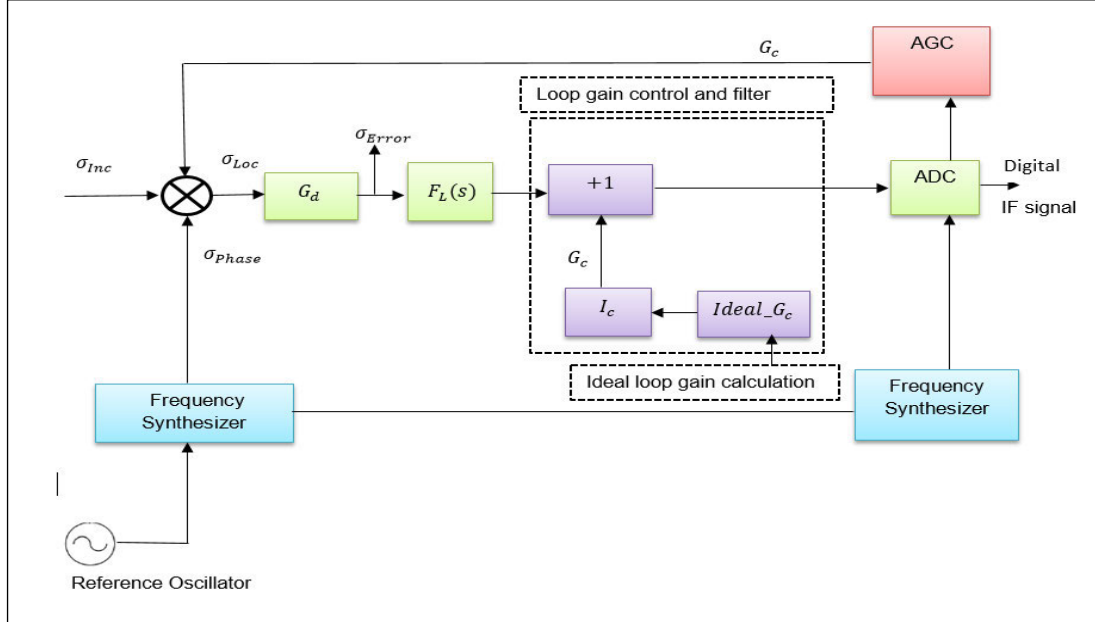


Figure 5.7: The loop gain calculation and modelling of the GNSS receiver.

It has been stated above that the purpose of this chapter is to investigate the sources of the signal degradation in the receiver. In figure 5.7 above, the Phase Locked Loop (PLL) function integrated into the AGC that is used to generate the sine wave for the local carrier phase that is similar to the incoming carrier phase. Through observation of the carrier phase generated locally, the incoming carrier phase is measured to determine if the PLL is in the lock state.

In Figure 5.7, the σ_{Inc} is the incoming carrier phase, σ_{Loc} denoted the locally generated carrier phase, σ_{Error} is the loop gain carrier phase error and σ_{Phase} is the phase error. The PLL uses three numerical stages to track the carrier phase of the received signal and compare it to the locally generated carrier phase. The first order is used to track the phase dynamics of the incoming GNSS signal. The second order of LF is used to phase error neglecting the steady state error that is caused by the velocity in relation to the satellite and receiver movements.

The third order of LF integrated to second order track the inputs of the acceleration in relation of receiver and satellite movement neglecting the steady state error. The tracking of the velocity and acceleration is shown in Figure 5.8 and 5.9.

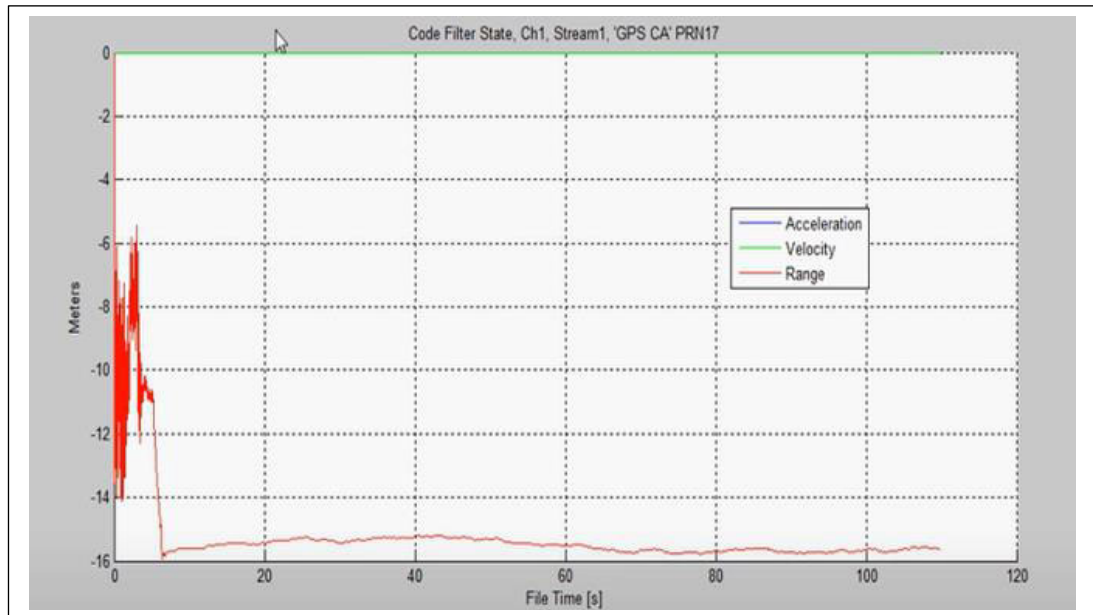


Figure 5.8: The code filter for GPS C/A: Range, velocity and Acceleration.

The loop filters are fed with a different phase to filter the thermal noise and further generate the control signal for the Numerical Control Oscillator (NCO). In the beginning of the observation, the range of the code filter state is high, and at about 60 seconds it starts to decline and become steady.

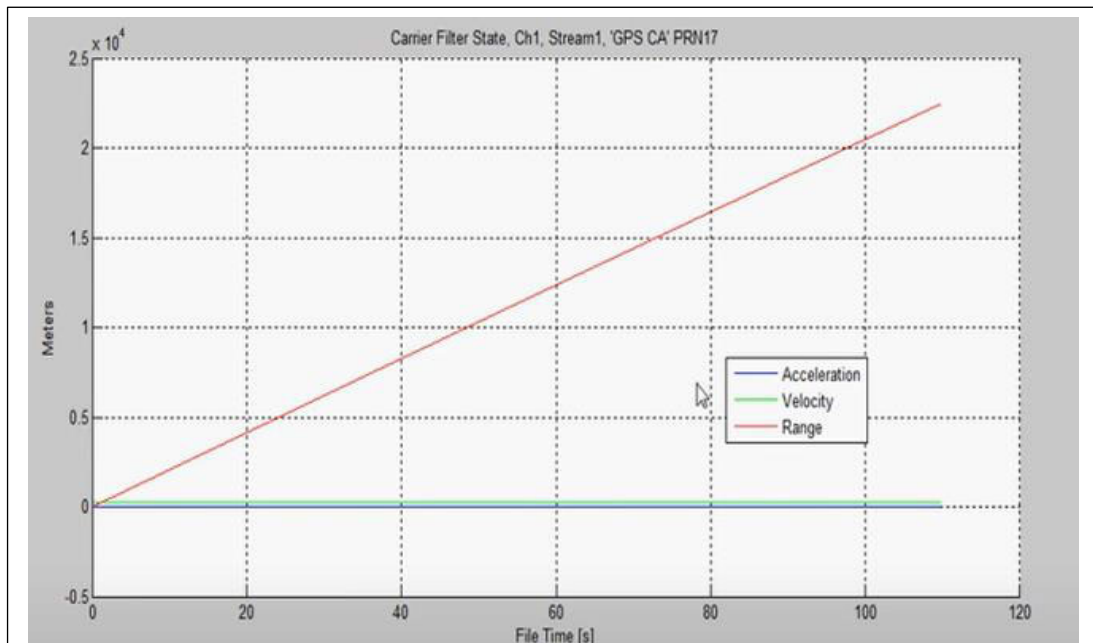


Figure 5.9: The carrier filter for GPS C/A: Range, velocity and Acceleration.

The NCO is incorporated into the GNSS receiver to transform and adjust the local carrier phase to ensure that the local carrier phase is aligned to the incoming carrier phase accurately. In this case, the range of the code filter state behaves differently. In the beginning, it is at zero, and it increases rapidly as the time increases.

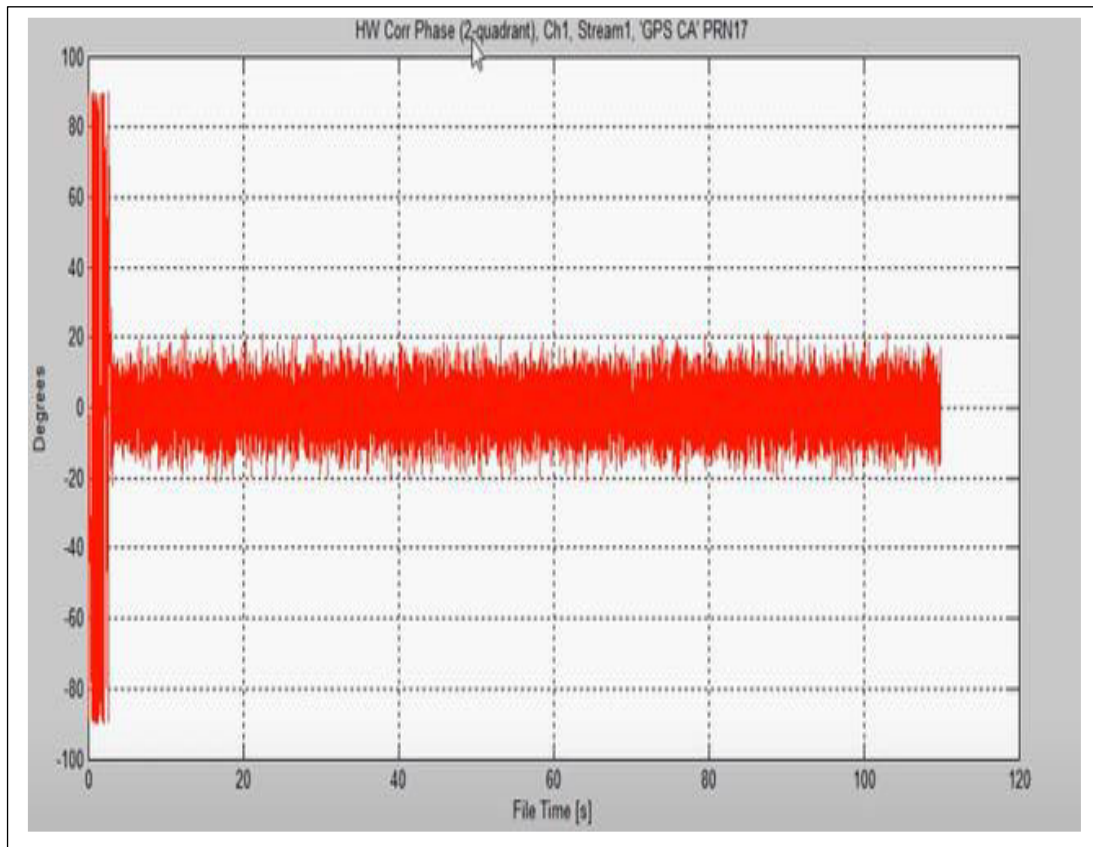


Figure 5.10: The correlation phase of the signal in the 2nd quadrant for GPS. In Figure 5.10, the loop gain is adjusted directly after passing the inertia elements to control the level of the thermal noise that contribute towards signal degradation at the receiver level. It must be noted that Figure 5.10 shows the agreement of equation (5.13) for infinite bandwidth, the AGC loop filter, and the spectral power of the incoming signal. The diversity of the GNSS receiver is caused by the differences in data resolution and default configuration. The user settings allow the loop gain to be adjusted to match the level of the noise in the incoming signal.

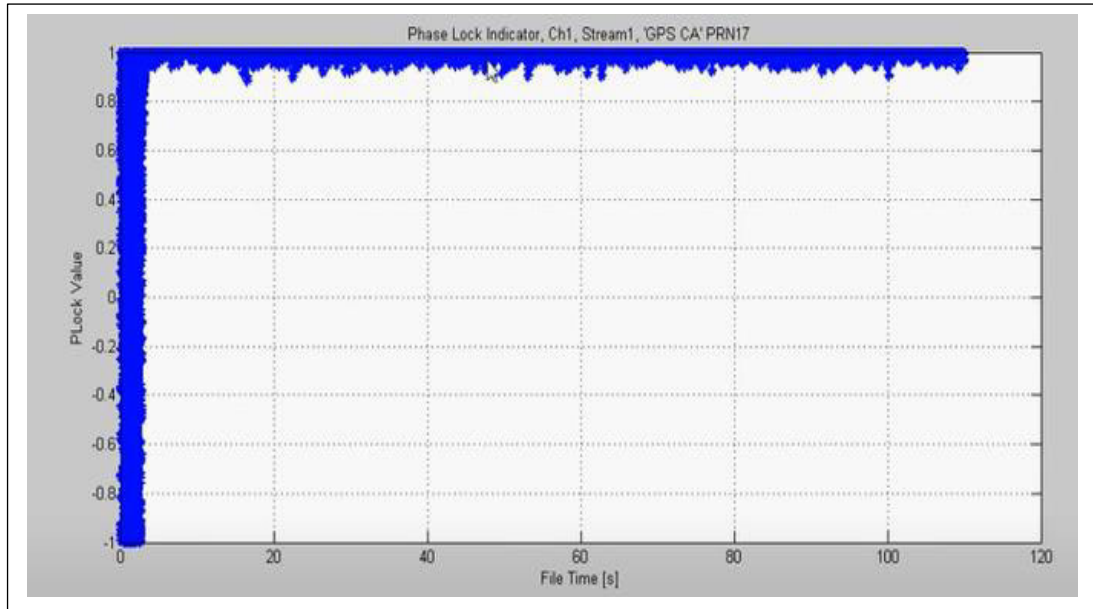


Figure 5.11: The illustration of the phase lock indicator for GPS C/A.

The inertia element is responsible for controlling the rate at which the loop gains changes. In Figure 5.11, the phase lock indicator is shown. The data variation observed in Figure 5.11 will be used to estimate the carrier phase error and the discriminator output. The discriminator output of the phase lock indicator is further used to compute the possible carrier phase tracking errors. To obtain the analysis in Figures 5.10 and 5.11, the discriminator output must reflect the locking conditions of the PLL if estimating the carrier phase.

The adjustment in the loop gain will introduce some disturbances in the tracking loop, and it will delay recovering from the locking state. To avoid the delay, the inertia is there to adjust the loop gain smoothly in a way that the disturbance will be eliminated without being noticed.

5.4.3. Detection of the new multipath signal

In the context of CSD, there is a possibility of the additional signal multipath that might not be detected since the number of multipath is not fixed along the space channels. The multi signals GNSS receiver used is capable of estimating additional multipath components after each signal bit transition cycle. Hence, in this research work the Generalized Likelihood Ratio Test (GLRT) is used to search for the possibility of the new path. The GLRT is capable of further updating the refining stage of the GNSS receiver with the output.

Hence, the GLRT uses two strategies to determine the threshold of signal detection. In the beginning, the GLRT consider the known multipath parameters that were previously detected to examine if there is an existence of the new path in the incoming signals. Secondly, the least value of the multipath parameters is considered as the troubling parameters to detect all possible changes in the signal. From the multipath model in equation (5.16), the a_k , ξ_k and τ_k represent the parameters of the amplitude, phase shift and time delay all consistent to the M^{th} paths of the direct signal path where $a_k = 1$, $\xi_k = 0$ and $\tau_k = 0$. The $\xi_k(t)$ is the direct baseband for spread code spectrum that carries the bits of the navigational data for the correlated signal with the local replica of the spectrum spreading code. The model is anticipated to be coherently integrated over chip and the sampling rate is $\frac{1}{T_s}$ and statistically expressed:

$$y_c(\tau) = \sum_{l_k=1}^{M_k} a_k \Re(\tau - \tau_k) + w_k(\tau) \quad (5.16)$$

Where the $\tau = 0, T_s, \dots (\mathcal{L} - 1) T_s$, a_k is corresponding to $A_k e^{j\phi_k}$ the coefficient of the complex path, $\Re(\tau)$ denote the PNR codes ideal autocorrelation function for the specific period or time T_p and the $w_k(\tau)$ is the function of the noise in output of the correlator that is governed by the variance of δ_k^2 . The signal multipath parameters are anticipated to be unchanged throughout the integration period of the channel and the matrix format is expressed as:

$$y_k = G_k a + w_k \quad (5.17)$$

Where the y_k denote the vector of the sampled signal $y_c(\tau)$ with the periodic length of $N_k = \frac{T_p}{T_s}$ and the:

$$a_k = [a_1 a_2 \dots a_M] \quad (5.18)$$

The vector of the w_k with the length of N_k denotes the vector of noise in the sampled signal with the matrix of $\Re_k$ and G_k . Statistically presented by:

$$G_k = [\Re_{\tau_1} \Re_{\tau_2} \dots \Re_{\tau_M}] \quad (5.19)$$

This function is further used to express the sampled version of the $\Re(\tau - \tau_k)$ and is expanded and expressed as:

$$\Re_{\tau_m} = [\Re(0 - \tau_m) \Re(T_s - \tau_m) \dots \Re((\mathcal{L} - 1)T_s - \tau_m)]^T \quad (5.20)$$

The synchronization of the GNSS receivers can sometimes be derived using the ML principle to the GNSS signal received from the space, regarding to phase shift and time delay estimation. The sampled parameters of the GNSS signal is anticipated to be separated from the rest of the data so nit does not interfere with the periodic data sampling, de-spreading and processing. The possibility of the new multipath is denoted by $(m_k + 1)$ and these multipath parameters are linked to the previous detected multipath components. The new multipath components are present if the GLRT passes the threshold values of the hypothesis (h_1) illustrated in equation (5.21)

$$\text{GLRT} = \frac{P(d, a_{k,m+1}, a_M | h_1, \dots, \hat{a}_{k,m+1} | h_1)}{P(d, a_M | h_0, \dots, \hat{a}_{k,m+1} | h_0)} > \gamma_1 \quad (5.21)$$

The approach of GLRT support the direct selection of the path parameters corresponding to the maximum correlation values. The statistic variable in equation (5.33) denote the complex Gaussian random variable performed in two hypothesis is shown.

$$\mathcal{J}_s = \mathbb{A}(0, \delta_{m+1}^2) \text{ under hypothesis } (h_0) \quad (5.22)$$

$$\mathcal{J}_s = \mathbb{A}(\mathcal{X}_{m+1}, \delta_{m+1}^2) \text{ under hypothesis } (h_1) \quad (5.23)$$

The algorithm in equation (5.21), is tested under two conditions shown in equation (5.22) and (5.23), respectively. This is carried out to detect the new multipath component. Recalling the multipath model in equation (2.11), if there is a new multipath signal detected, there will be no autonomous relationship between the signal components, the amplitude, delay and phase for the peak values of correlation.

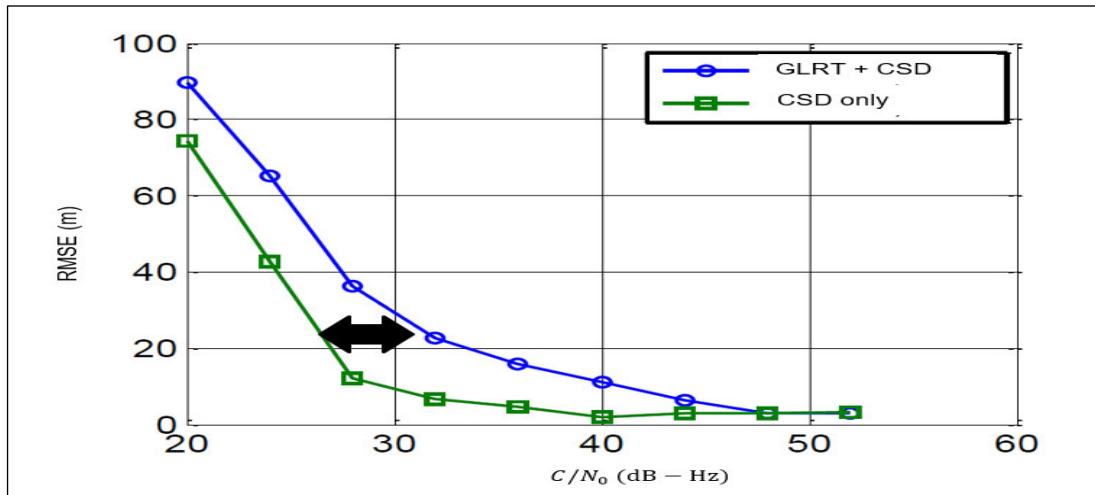


Figure 5.12: The performance evaluation for GLRT+ CSD and CSD only techniques.

Figure 5.12 illustrate the comparison between the GLRT +CSD and CSD only. The inclusion of the CSD to the GLRT improve the power level of the signal in the test results. Hence, the signal can travel over the long distances with minor losses anticipated in the process.

5.5. Summary and conclusion

This chapter examined the signal degradation in the GNSS receiver caused by thermal noise, as well as the advanced signal tracking integrated into AGC. This chapter presented the novel of the loop gain control for PLL in GNSS receivers to minimize the impact of the thermal noise in the signal. The thermal noise in the incoming signal is not the only problem in GNSS applications. In chapter four, issues such as signal multipath and distortion along the satellite have been addressed by adopting the CSD methodology. Hence, the noise, acquisition, and tracking uncertainties, the code Doppler, and data message effects were not addressed. The PLL and AGC are integrated to improve the tracking function and ensure that there is no or minimum noise that passes through to digital processing. The AGC is used to minimize received signal amplitude losses; if the incoming signal is completely buried by thermal noise, the AGC will measure the noise level and adjust the amplitude of the signal to make it compatible with analogue to digital conversion. Chapter six, investigate the performance and capabilities of the signal mitigating methodology in the context of multi-signal GNSS receiver as proposed in chapter four.

CHAPTERS SIX

Investigating the performance of the CSD and the multi-signal GNSS receiver

Chapter six provides the critical aspect of this research work, where the performance of the CSD and the multi-frequency GNSS receiver is investigated to ensure that the concept will be valuable across the applications that use GNSS.

6.1. Background

The CSD is introduced and implemented in chapter four. The CSD is designed to reduce the impact of a multipath signal if the GNSS receiver is located in an area with signal obstructions. In order for the receiver to calculate the satellite coordinates at any location and time taken for the signal to reach the receiver, the GNSS satellites in space require one or more frequencies to transmit the navigation data and the ranging codes in relation to GNSS applications. These are crucial parameters to start with when dealing with the architecture and processing techniques of the GNSS receiver. The multi-signal GNSS receiver is capable of processing the GNSS signal that holds the following main components:

- The signal carrier—from the carrier, the GNSS receiver will be able to identify the origin of the signal in terms of frequency band or link and satellite constellation.
- The navigation data – this is a form of the binary coded messages to provide the satellite ephemeris data, satellite status and clock bias considerations
- The ranging codes and signal modulation—this is also known as the PRN codes—further ease the estimation of signal propagation from space to the receiver. This is the spreading code, also called a chip, and it does not hold additional data beside the time taken for satellite-to-space propagation.

The GNSS signals differ in terms of their frequencies, structure, modulation technique, availability, and trustworthiness. Hence, if the GNSS receiver is capable of multi-signal processing, there will be more data ingress and accurate output. This section will present the performance of the CSD, the functional block diagram of the multi-signal GNSS receiver, and the multi-GNSS acquisition and tracking.

6.2. The analyses of the GNSS multi frequency and constellation.

This is the capacity of the GNSS receiver to process and handle the multiple signals from the multiple satellite constellations simultaneously. The adoption of the multi-frequency receiver is the most effective methodology to separate the ionospheric errors from the signals. The ionospheric error fluctuates with the frequency and structure of the signal. Hence, it affects the GNSS signal uniquely. The ionospheric error is estimated by comparing the delay between two incoming signals. The interest of the research work is to adopt the CSD using multi-frequency receivers, more especially for modernized and new GNSS signals for GPS and Galileo. GPS and Galileo use wideband frequency links L-5 and E-5a, which provide inherent multipath and noise reduction capabilities. In the case of L-5 and E5a, the receiver combines these signals to remove the ionospheric error. Furthermore, the multi-frequency receivers are more immune to signal intrusion along the satellite path. On the other hand, the multiple constellations ensure that there are numerous satellites in view of the GNSS receiver. The rule of thumb is that the GNSS receiver needs at least three satellites in view to calculate the desired PVT precisely. The multi-constellation has the following advantages:

- The accuracy of the position, velocity, and time calculation is enhanced.
- The duration for signal acquisition is reduced for all accusation methodologies.
- The propagation difficulties caused by the foliage and buildings are reduced significantly.
- The dilution of GNSS precision is improved due to the enhanced spatial distribution of the observable GNSS satellites.

If the GNSS receiver is capable of handling satellites from a variety of constellations, signal redundancy and precision are built into the PVT solution (for example, if the propagation of the GNSS signal is blocked due to buildings, there is a possibility that the GNSS receiver will pick up the signal from alternative GNSS constellation.)

The signal spreading codes are known as the PRN, as stated above, because of their noise-related properties denoted by their low cross-correlation values with other signals and very high autocorrelation values. The GNSS data bit must be synchronized with the spreading code duration from the beginning of the processing. There may be multiple reiterations of the PRN codes for one data bit in the processing in some cases. Hence, the spreading code is likely to be generated by the Linear Feedback Shift Register (LFSR). The GPS and Galileo satellites have the following spreading codes.

- The GPS L-1 C/A uses the spreading codes that belong to the gold codes and are generated by the shift registers with the length of 1023 chips.
- The spreading codes of the Galileo E1 signals are stored in the GNSS receiver memory and are called memory codes with a length of 4092 chips.

GNSS assistance is the functionality that is embedded in the multi-frequency GNSS receiver to simplify the signal acquisition process. Therefore, the estimated PVT solution for the GNSS receiver and the intermediate frequency for the front end are provided as an input to the acquisition block. The ephemeris assistance is normally provided in a RINEX file format for navigation data.

Using the ephemeris, the Doppler frequency for each satellite in view can be estimated, and it can further assist to narrow the window for frequency search to improve the signal acquisition process. The PRN code modulation of the traditional GPS L-1C/A signal is called BPSK because the spreading codes are in the form of a rectangular shape with a length that is equivalent to the PRN code chip. The recently developed GPS and Galileo signal uses a typical modulation scheme called BOC modulation because the spreading codes are continuously multiplied and are in square wave format. The waveform frequency is 1.023 MHz. The significant details of the cross-correlation and autocorrelation for GPS and Galileo with the Doppler frequency f_D between -10 kHz and 10 kHz are presented in Table 6-1.

Table 6-1: The characteristics of GPS L-1 C/A and Galileo E1 correlation function for CBOC modulation scheme

Doppler Frequency [f_D]	GNSS signal Autocorrelation		GNSS signal cross correlation		
	Galileo E1	GPS L-1 C/A	Galileo E1 Identical satellite	Galileo E1 Diverse satellite	GPS L-1 C/A
$f_D \in = 0, -10$ kHz	-25.39 dB	-23.94 dB	-26.66 dB	-24.49 dB	-23.94 dB
$f_D \in = 0, 10$ kHz	-23.44 dB	-19.18 dB	-25.16 dB	-22.82 dB	-19.08 dB

The GPS L-1 C/A signals have the lowest spreading code adhering to their chip number, since the chip length is 10230. The Galileo E1 has the memory code of 4092 chip. The GPS L-5 signal has a frequency link of 1176.45 MHz with an increase of 3.6 dB compared to the GPS L-1 C/A signals. Hence, the chip rate of GPS L-5 is high, and it allows for improved tracking performances. The data component of the GPS L-5 has a secondary code that is equal to 10 bits, which is suitable for one-bit data, and the civil signals of the Galileo and GPS have a data bit duration that is much lower than the data bit duration of the GPS L-1 C/A. The modernized GNSS signals have the longer spreading code and the properties correlation function is improved significantly. The Doppler frequency of the Galileo E1 signals ranges between 0 Hz and 10 kHz, with the maximum value of autocorrelation being around -23.41 dB, which is 4 dB superior to the GPS L-1 C/A for autocorrelation isolation point. The GPS L-1 C/A autocorrelation isolation is located at -19.18 dB. The modernized GNSS signals have a high data bit duration and data rate, which is also known as the binary categorization of the data component for GPS L-5 signals. The dual components of the modern GPS signals indicate the adaptation of the modified acquisition methodology in the signal structure. The acquisition methodology is categorized by the existence of the binary sequence for both components, and their data bit period must resemble the period of the spreading code.

There are two signal acquisition methodologies that were developed over the past few years, coherent and non-coherent integration. The Galileo E1 has about 50% of the signal power accessible, which is equal to a loss of 3 dB. This research work is interested in the acquisition of the data component only; hence, the non-coherent integration is used and illustrated in Figure 6.1.

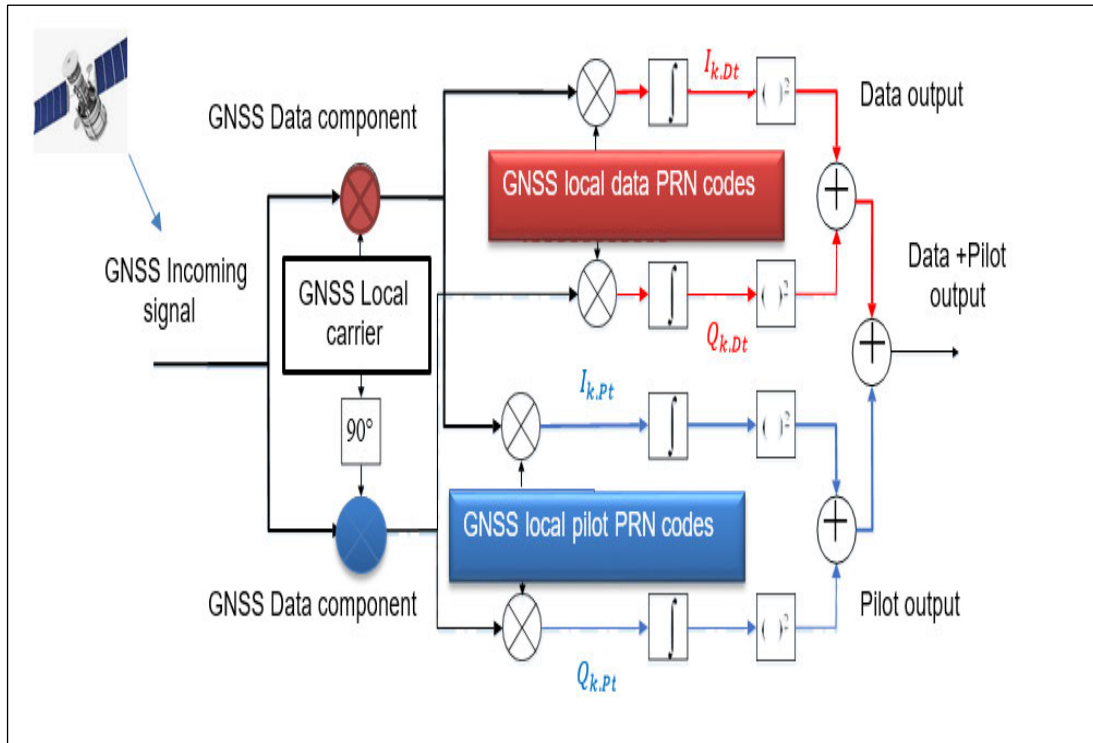


Figure 6.1: The acquisition block of the innovative GNSS receivers.

In Figure 6.1, the acquisition of the recently developed GNSS signals is illustrated; the incoming GNSS signal is correlated independently with the local replica of the data component and the local replica of the pilot component. The output of the pilot component will be ignored. It was previously assumed that, the probability of bit transition is about 50% for the occurrence of bit transition. The duration of the data spreading must be shorter or equivalent to the period of data bit transition. The bit transition will be different from 50% because of the secondary codes on the data component. However, this is no longer possible for the modern generation of GNSS signals due to the dual components of the signal.

6.2.1. Multi-GNSS acquisition

The adequate numerical algorithms for GNSS signal acquisition are comprehensively defined in [200] and [201]. The concept of CSD requires a GNSS receiver that will be capable of multi-GNSS signal acquisition between the GPS and Galileo signals. The acquisition methodologies for Galileo and GPS are similar and make use of the FFT based on the parallel code phase search. The multi-GSS acquisition has configurable parameters for the search window, the signal threshold, and the non-coherent integration rounds. There are two modes that exist in the multi-GNSS acquisition, the aided and unaided modes, and the threshold values are configured separately. The Galileo E1 data and pilot channels have data bits and spreading codes that are between 3 and 4 ms long. As a result, in order to achieve long non-coherent integration, the possibility of bit transition between successive epochs must be considered.

6.2.2. Multi-GNSS tracking

After completing the multi-GNSS acquisition for all parameters of the received signals, the detection of the data bit edges is executed for all satellites in view that belong to different constellations. There are separate tracking channels for each data bit edge that is detected during the process. If the data bit edges are for signals from different satellites, the multi-GNSS tracking will begin with the correlation interval for code length. If all signals are from similar satellite constellations, the normal signal tracking process will be initiated. The intervals for code length are dependent on the system, 1 to 2 ms for GPS and 4 ms for Galileo. This implies that the tracking of the GPS signals is done in every 1 to 2 ms of information, and the tracking of the Galileo is done in every 4 ms of information. This is because of the different code epochs in terms of their length.

6.2.3. Multi-correlator tracking

Two correlator parameters are configurable from default settings to user specifications. These parameters are for tracking and monitoring the noise level during the signal processing from signal acquisition to correlation.

If the detected data bits are from similar satellite constellations, the normal correlation will be initiated, and if the data bits are from different satellite constellations, the cross-correlation will be initiated. The cross-correlation is adequate for a simultaneous signal process. The spacing of the tracking is configurable if required, but the default value is 0.25 chips depending on the design of the receiver.

6.3. The acquisition to tracking transition of the GNSS signal

The signal acquisition is the core step of the signal processing in the GNSS receiver, especially if the receiver is exposed to multiple constellations. The aim of the GNSS signal is to ensure that the signal tracking is carried out successfully and further ensure that the right cells are detected and validated against the carrier-to-noise density ratio C/N_0 . The GPS L1C/A is the signal that uses the Frequency Lock Loop to estimate the frequency. Hence, the Phase Lock Loop is locked. For the recent GNSS signals, the long integration period is required for the data component during the tracking process, and the secondary code should be acquired from the navigation data.

6.4. Modelling and results discussion

In this section, the performance of the CSD is evaluated through a series of analyses and discussions. Figure 5.2 depicts the functional block for a multi-frequency receiver with a focus on GPS and Galileo signals. The GNSS receiver illustrated in Figure 6.2 is intended for post-processing of the GNSS signal and real-time operation. For simulation purposes, the receiver is capable of storing the immediate data obtained from the acquisition and tracking to the pre-saved information file for offline processing.

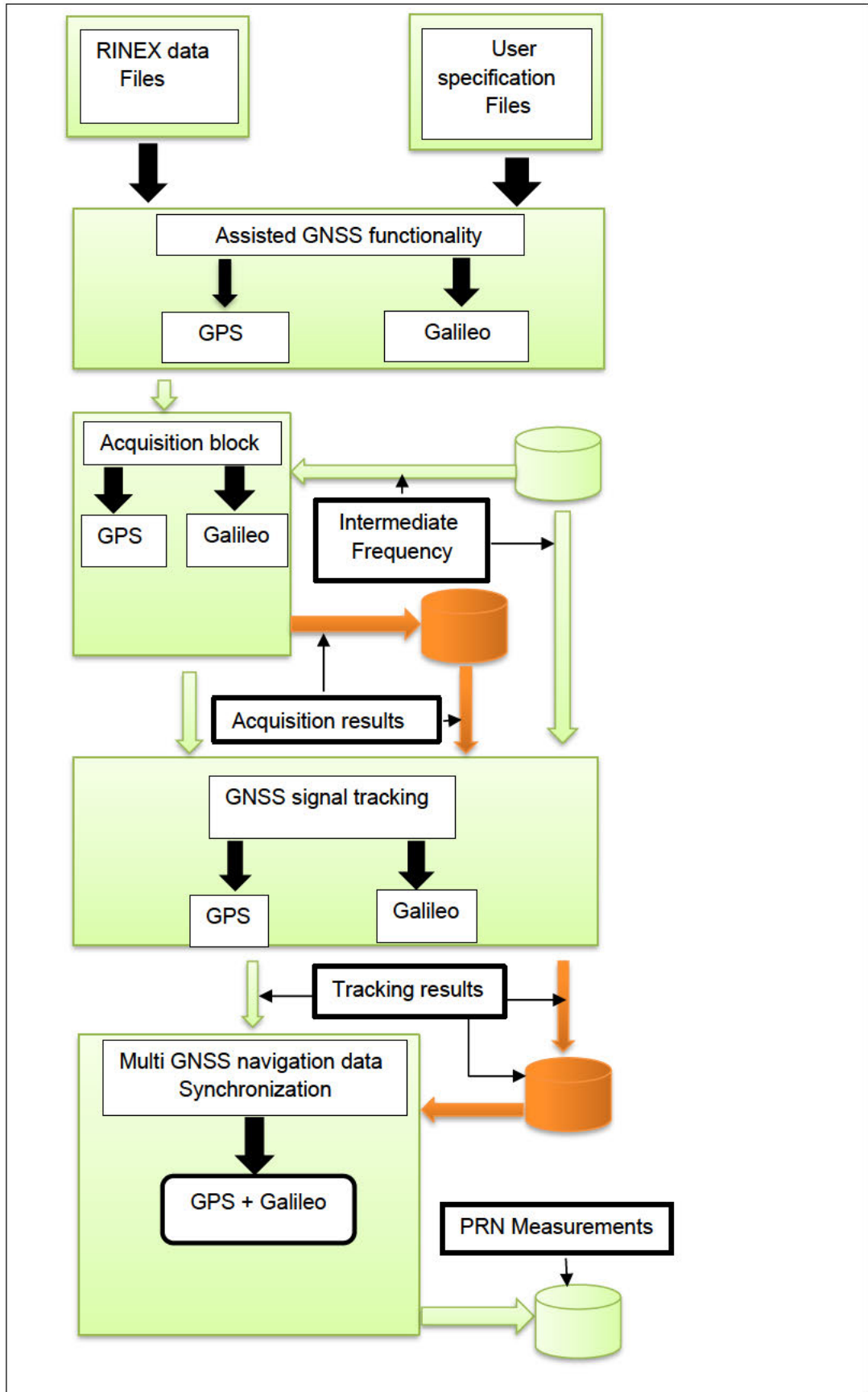


Figure 6.2: The post-processing of the GNSS signal and real-time operation.

The assisted GNSS functionality is dependent on user parameters extracted from the pre-saved file system and the optional receiver independent format known as RINEX navigation files. These files are used to determine the processing of the Intermediate Frequency (IF) to simplify the processing of the radio frequency (RF) on the front end. The signal acquisition can be performed by means of the IF data that is kept on the file system, if this is requested by the user. Hence, the results are stored in the computer memory. On the other hand, the signal acquisition can be bypassed by retrieving the already stored acquisition data, depending on the accuracy requirement for the user. The outcomes of the signal acquisition are similar, regardless of the acquisition methodology being used. The results of the signal acquisition are passed to the second stage, the tracking stage. The similar options mentioned for acquisition are available at this stage, and the output of the tracking is passed to GNSS navigation data. At a later stage, the PRN measurements are recorded. In this research work, the navigation data and the PRN measurements are used to evaluate the satellite availability. For multi-correlator tracking, the default configuration of the GNSS receiver has two correlation fingers used for noise level monitoring and tracking.

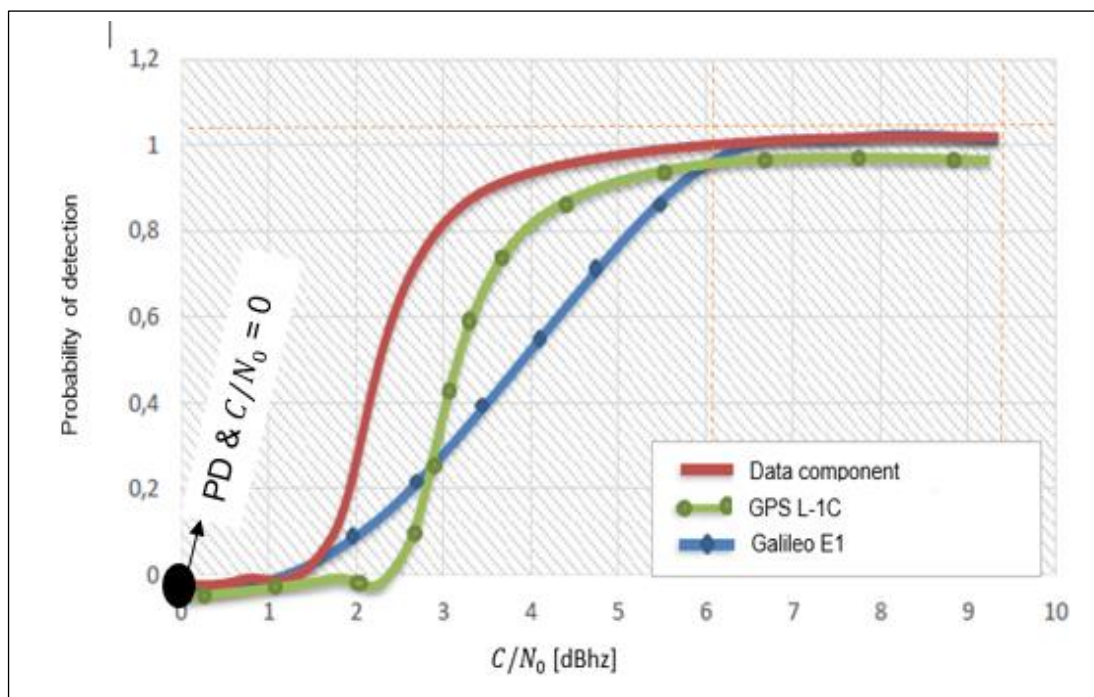


Figure 6.3 Probabilities of detection of GPS L-1C and Galileo E1 for data only.

From Figure 6.3, it is observed that the GPS L-1C and the Galileo E1 have an unequal distribution of the signal power and the carrier-to-noise ratio.

There are differences between them before reaching 6 dB of C/N_0 . After that, the probability of detection is similar and continuous. The probability of detection for the data component begins to grow rapidly from the C/N_0 that is between 1 and 1.5 dB, as illustrated in Figure 6.3. The correlator finger spacing is configurable based on the user requirements, and the default chip value is 0.25. The multi-correlator tracking is the feature that facilitates the window search of bit sign, spacing, and output rate at every stage and further analyzes the characteristics of the channel. The classic window of the multi-correlator output of the code delay is about ± 3 chips of the received signal. The secondary code can only go through the acquisition once the location first bit is identified and synchronized with the spreading code. The carrier frequency is tracked by the FLL using the frequency error obtained between the received and local signals. Hence, this is the classical feedback that contains the estimate obtained from the low pass filter and is further used to control the numeric controlled oscillator (NCO). During the signal acquisition, the local replica is always present. The local replica is situated in the filter and is called the "matched filter method," which is similar to the incoming signal. In the event that the GNSS signal uses the CBOC (6, 1, 1/11) modulation, the local replica will also use the CBOC (6, 1, 1/11). Therefore, a correlation between these signals is required. In the search stage, the acquisition approach is configured in a three-dimensional format to search the Doppler frequency domain, signal code delay and the number of visible satellites regardless of constellation. The search space for every satellite is determined by correlating the code generated locally and the received signal. The satellite search space is further used to cover the full range of a possible Doppler shift and time delay. The synchronization parameters of all visible satellites, regardless of the constellation, are estimated using the maximum power generated in the correlation stage.

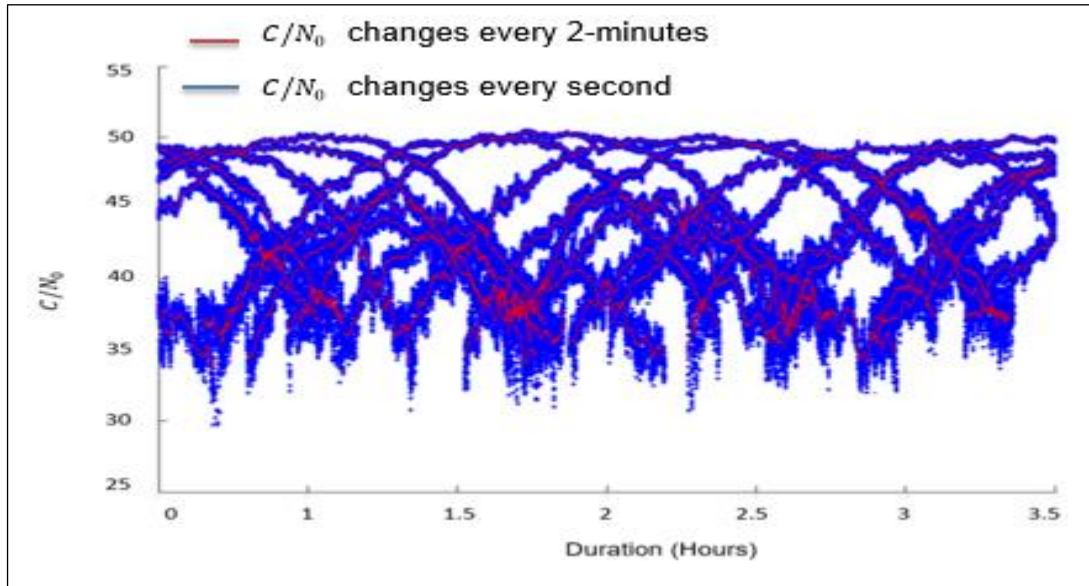


Figure 6.4: The C/N_0 for numerous satellites GPS L1 frequency band measured on the receiver.

In Figure 6.4, the C/N_0 of the GPS L-1C signal for more than three satellites is illustrated and measured on the multi-frequency GNSS receiver. The observation took about 3 hours and 30 minutes; the C/N_0 measurements for every second are represented by the blue print, and the measurements for every two minutes are denoted by the red solid lines. From the observation in Figure 6.4, it was pointed out that the PRN codes and signal Doppler are conserved after the data mixing and decoding stage, and the carrier frequency is reduced.

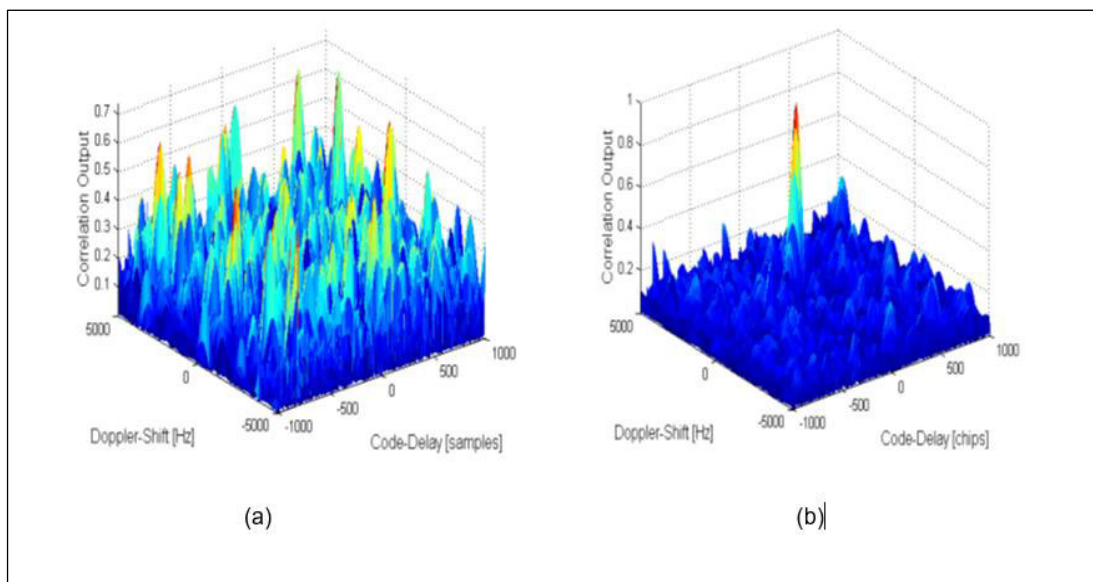


Figure 6.5: The correlation for visible and invisible satellites to the receiver.

The GPS satellite signals are buried in thermal noise at the IF stage, the Automatic Gain Control (ACG), and the analogue to digital conversion process is carried out in this stage. In Figure 6.5, there are two possible cases that are illustrated: (a) the visible satellite and (b) the satellite that is not visible to the receiver. The cases in Figure 6.5 (b) are also explained in terms of the SNR of the received signal from the satellite with low signal strength that is not detectable to the receiver. The maximum correlation power is exceeded in Figure 6.5 (a) for the GNSS receiver to detect the signal transmitted by the satellite in view. Hence, the established threshold is defined in terms of the anticipated probability of detecting false alarms during the acquisition. The SNR of the correlation peak is consistently averaged and monitored to improve the performance of the signal acquisition. In Figure 6.5, the transition for the (a) 1st and (b) 2nd bit signs are illustrated. Because the presence of a very weak signal is anticipated, this is a non-coherent integration. Hence, the correlation interval is larger than the period data component.

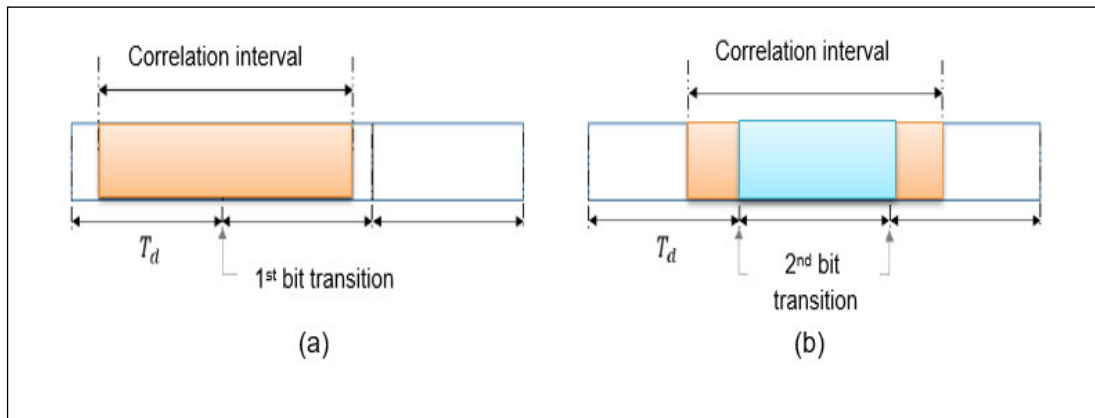


Figure 6.6: The data bit transition for 1st and 2nd transitions during correlation function.

There are effects along the data bit transition and losses caused by the sign transition that need to be reduced significantly by enabling the long, non-coherent integration. The best way to deal with data bit transition issues is to randomly choose values between +1 and -1 to square the numerical calculations performed during the acquisition period. The GNSS clock offset denotes the difference between the actual time and the imaginary time in the memory of the GNSS receiver. The GNSS clock offset against specific measurement indices is illustrated in Figures 6.6 (a) and (b).

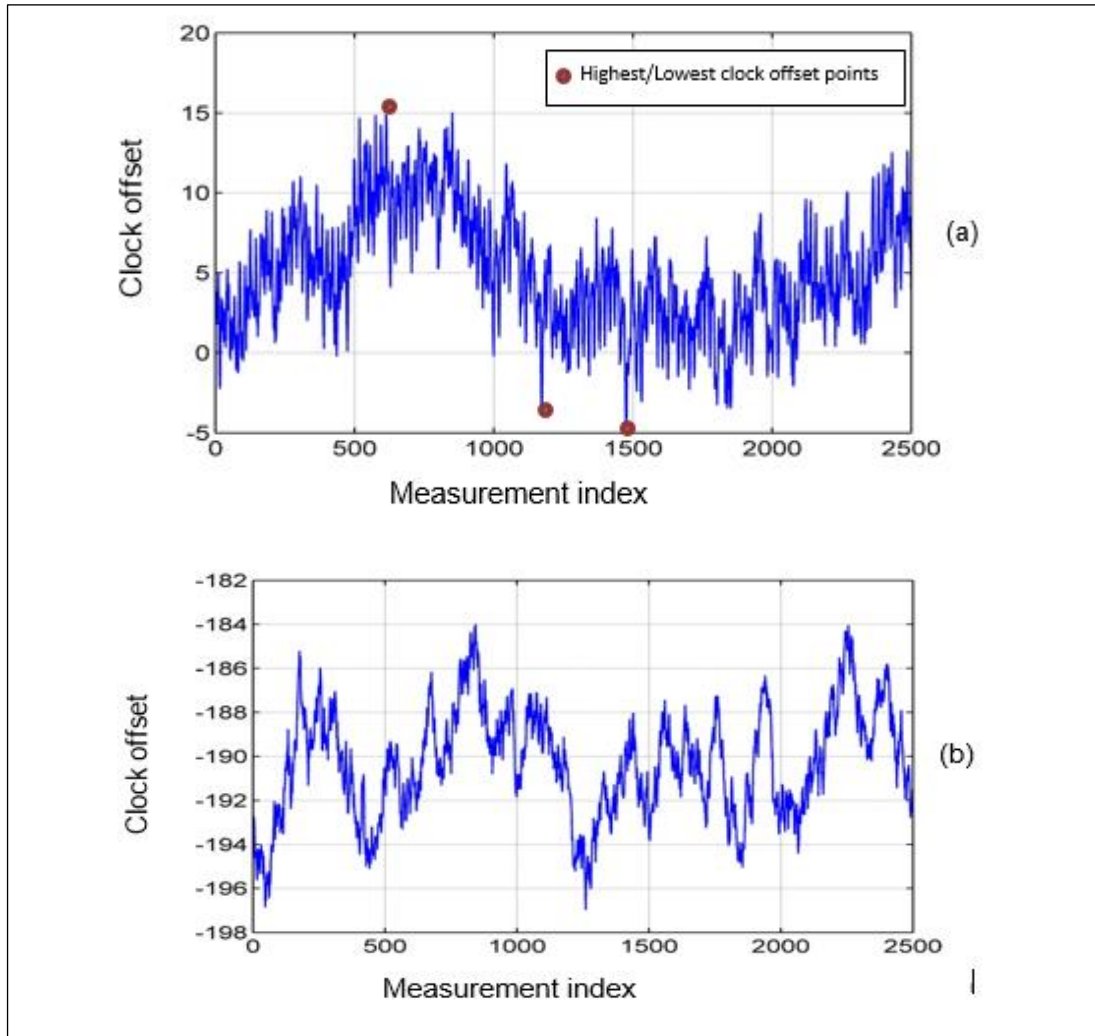


Figure 6.7: The GNSS clock offset: Lowest and highest clock offset.

In figure 6.7, the clock offset retrieved by the GNSS receiver is shown. From the observations, there is no significant difference between a multi-signal GNSS receiver and a single-frequency GNSS receiver. Figure 6.7(a) shows the anticipated clock offset between the GPS and Galileo signals for a multi-frequency GNSS receiver that is in a clear view without obstruction, and figure 6.7(b) illustrates the clock offset of the GPS and Galileo signals if the receiver is obstructed by foliage. From the observation, it is noticed that there is a leap second difference of 14 seconds if the visibility of the satellite to the receiver is obstructed. This observation was carried out for 10 hours and updated every 2 hours.

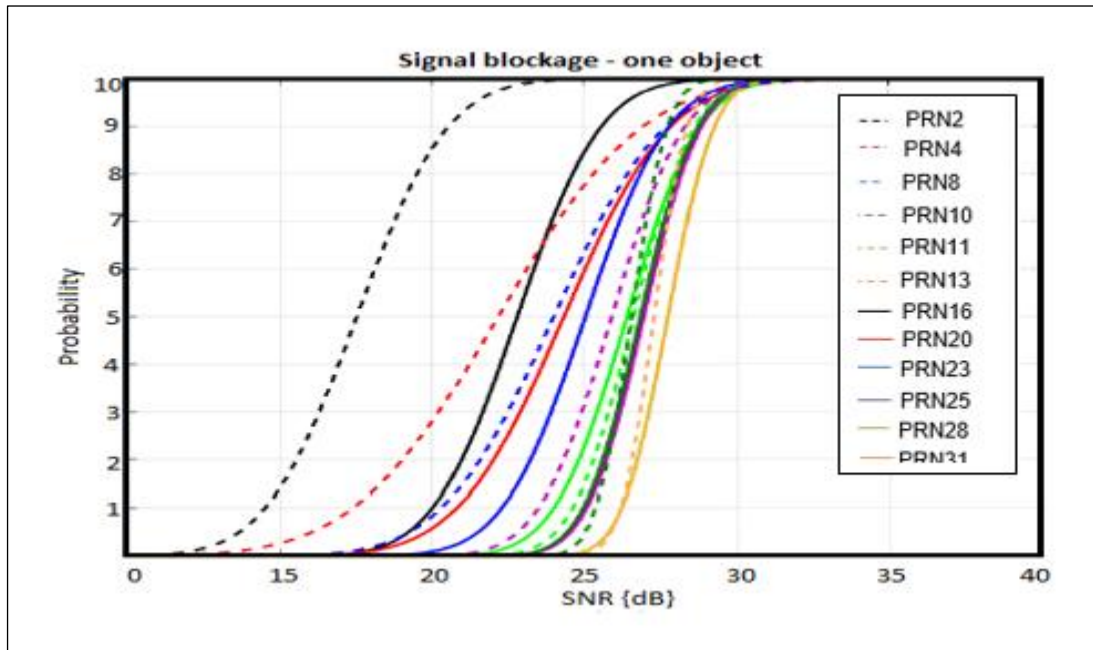


Figure 6.8: The illustration of the coherent integration against probability of detection.

When designing and configuring the parameters for signal acquisition, the C/N_0 maximum ranging between 25-45 dB-Hz is the maximum value targeted to reach. Hence, Figure 6.8 and 6.9 illustrate the probability of detection in relation to C/N_0 and non-coherent integration period.

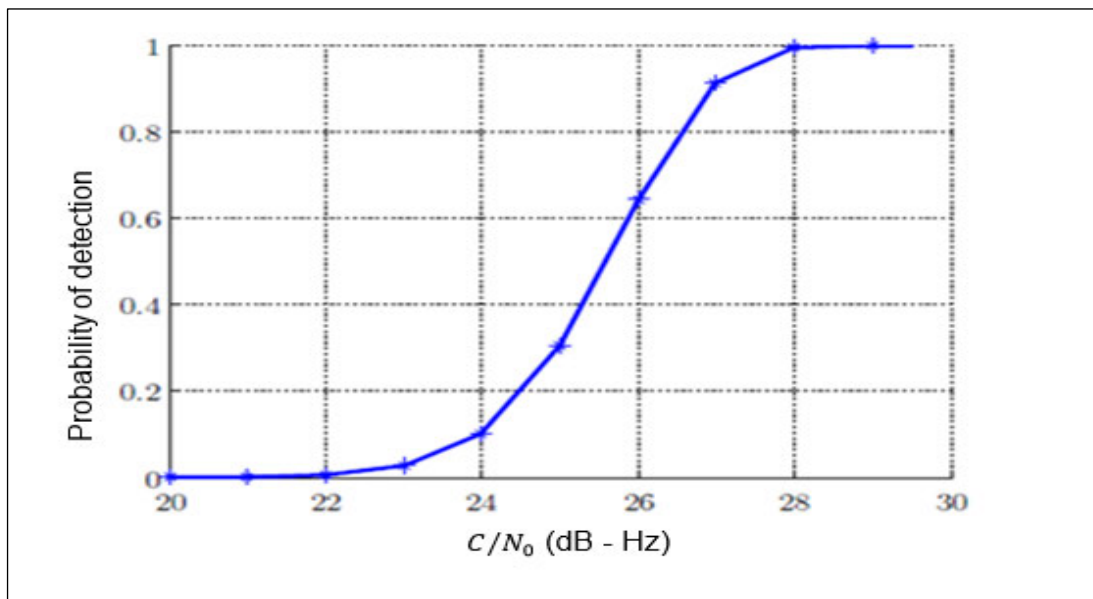


Figure 6.9: The changes of the C/N_0 due to the changes in detection likelihood.

The maximum C/N_0 , the 42 dB-Hz is about 93% of the margin and the in this value, the probability of detection is equivalent to one (1) for strong signal strength and for weak signals with single frequency, the probability of detection will decline and reach about 55% of the margin.

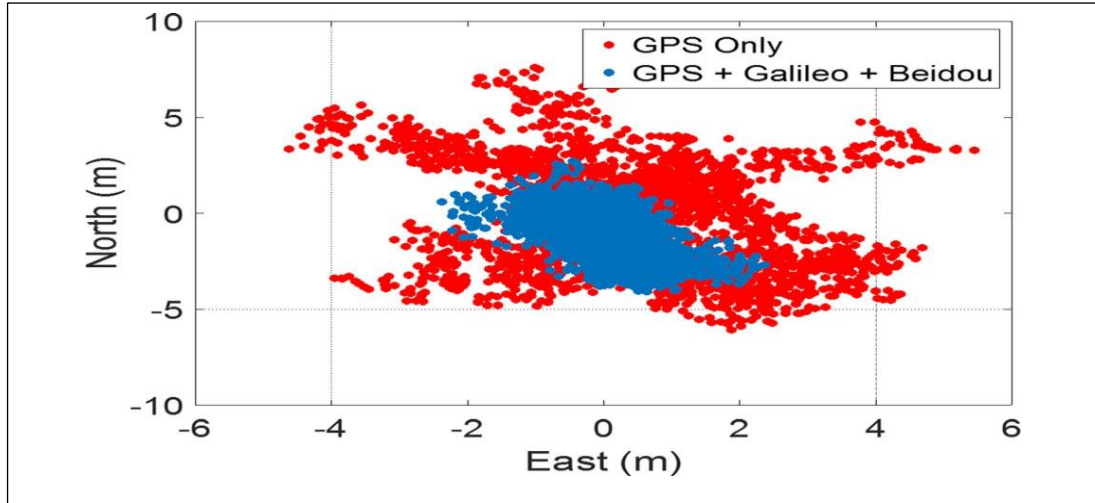


Figure 6.10: GPS only and Galileo+GPS+ BeiDou satellite visibility.

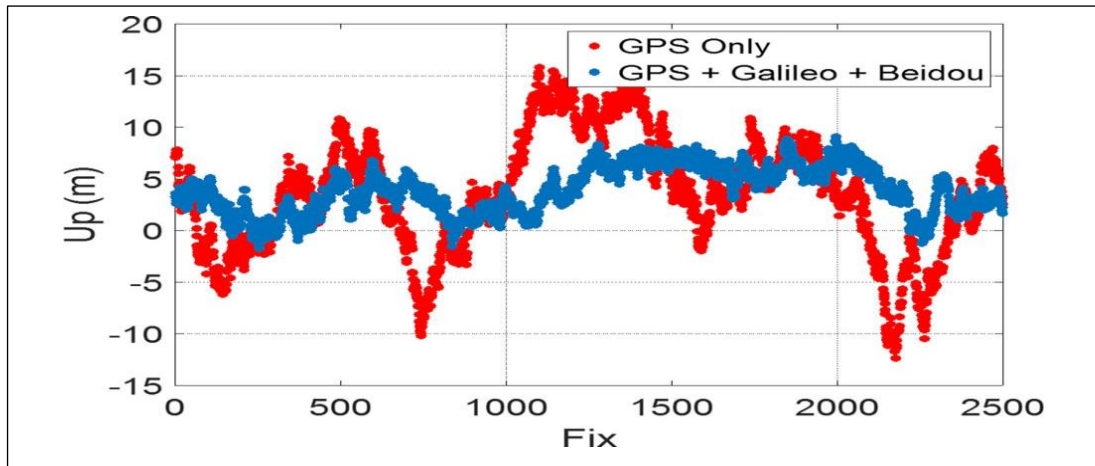


Figure 6.11: The visibility of satellite constellation (skyplot).

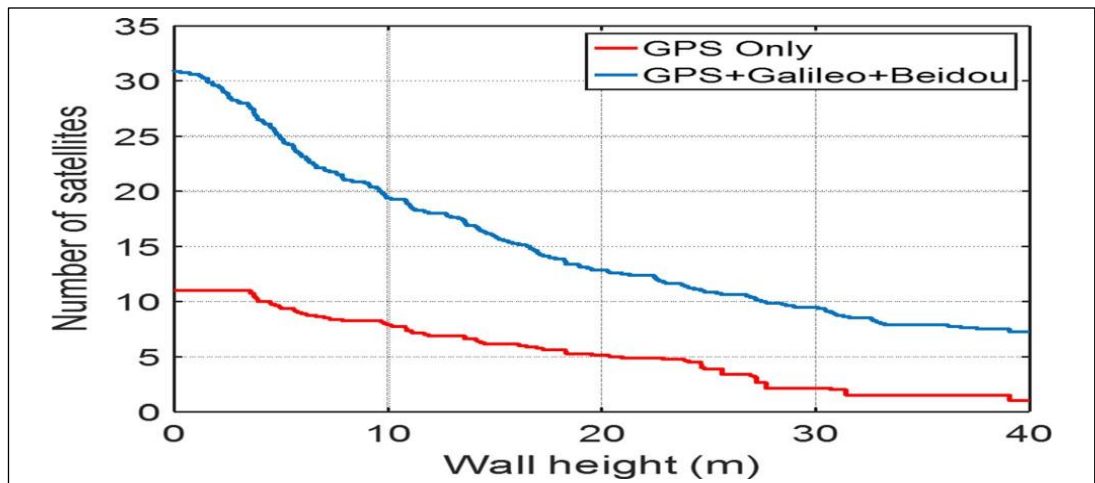


Figure 6.12: The number of visible satellites.

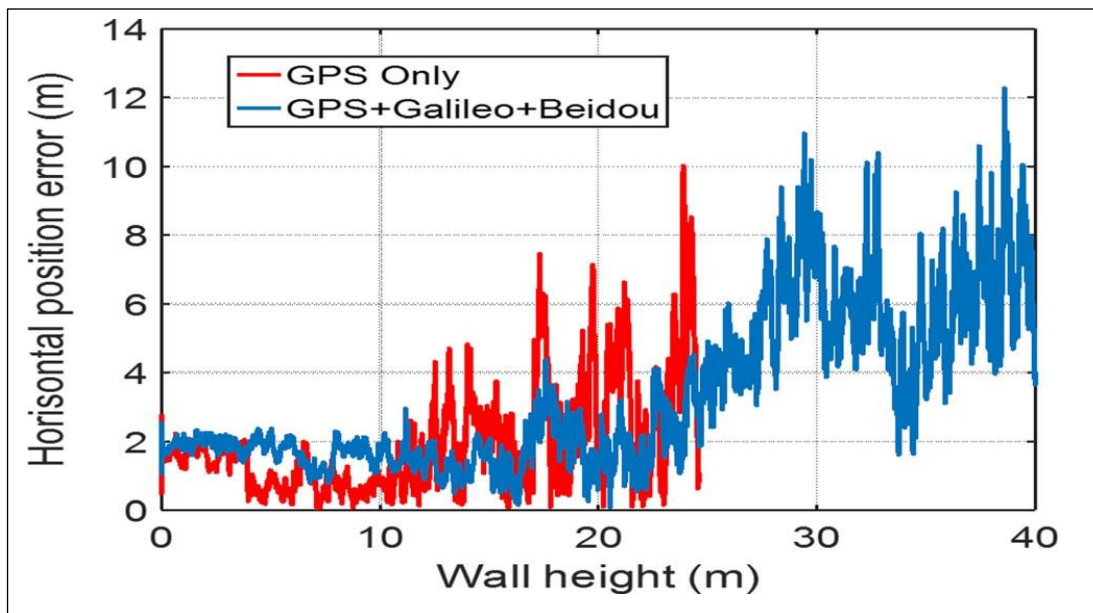


Figure 6.13: The illustration of the horizontal error for multi- constellation.

In Figure 6.13, it is further illustrated that, the complete number of the required non-integration for Galileo E5a is higher if compared to GPS CA codes, this is because, the code phase search for Galileo E5a is about 8-10 times larger than those of GPS CA codes. The PRN code length influences the code phase search of the E5a.

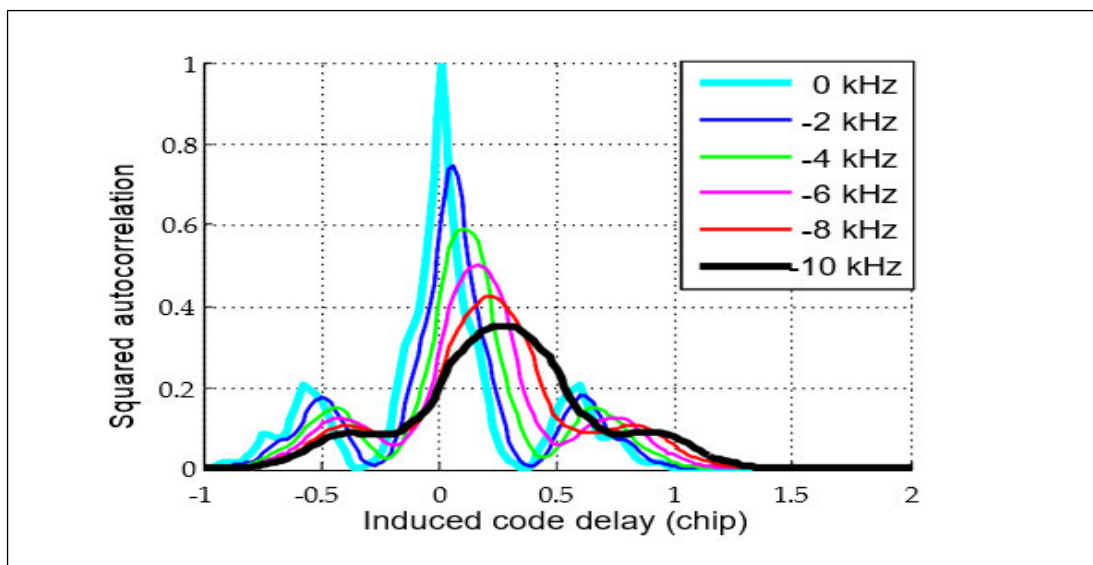


Figure 6.14: The Galileo E1 autocorrelation for code Doppler that is equal to 10 ms.

There are numerous cases to consider when dealing with the GNSS signal acquisition.

In some cases, the peak value of the correlation function is attenuated, and the acquisition detector used to estimate the GNSS signal parameters (amplitude, code delay, Doppler shift, etc.) is likely to not surpass the acquisition threshold value and will fail instantly. In Figure 6.14, the possibility of the acquisition detector crossing the threshold values is illustrated by the black curve of -10 kHz for incoming Doppler frequency. The GPS L-5 is the BPSK-modulated GNSS signal and has a quick chipping rate. The correlation peak offset of the BPSK is normally moved by one chip more in chipping rate for all incoming Doppler frequencies above 2 kHz, and the acquisition threshold outcomes encourage the autocorrelation for a specific induced code delay.

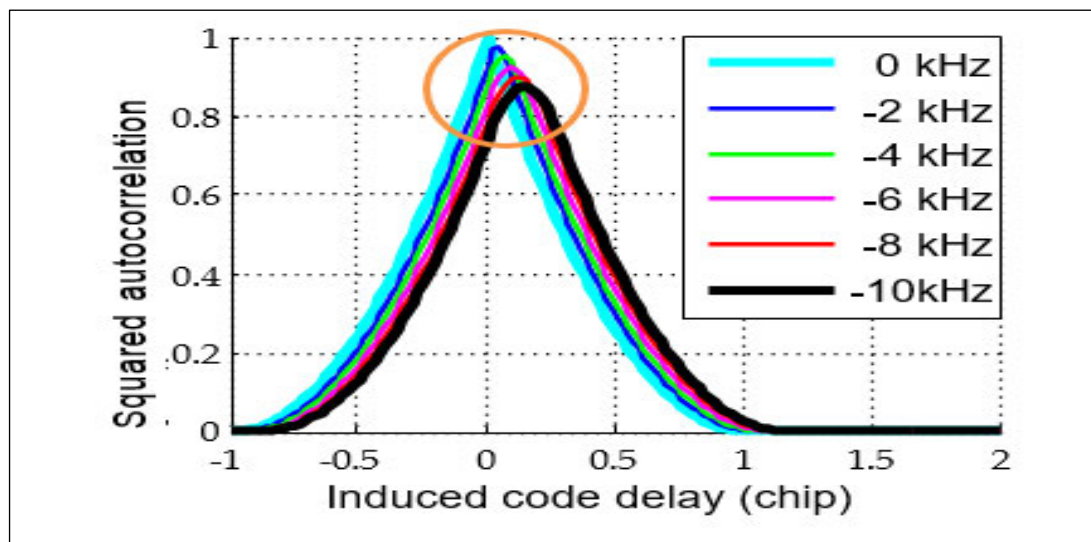


Figure 6.15 : The GPS L-1 C/A autocorrelation for code Doppler that is equal to 10 ms.

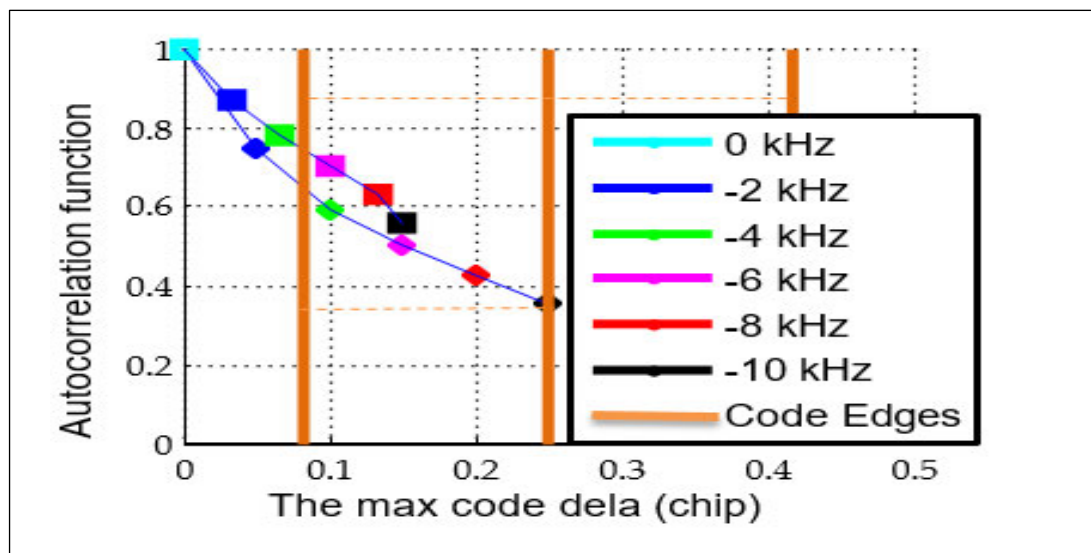


Figure 6.16 : The signal amplitude variation during autocorrelation.

Figure 6.16 illustrates the impact of the code Doppler on the standard value for the autocorrelation function. The negative Doppler frequency for the incoming signal has the positive code delay induced for GPS L-1 C/A. The color cyan represents no Doppler frequency, and the worst scenario is black with an incoming Doppler frequency of -10 kHz. For GPS L-1, the amplitude of the maximum values is reduced drastically to shift the peak of the induced code delay. It can be observed in figure 6.16 that over 150 ms there is a shift between 0.75 and 0.82 chip between the incoming signal and the replica signal for the Doppler frequency of 10 kHz. The autocorrelation function will reach its maximum if the induced code delay is 0.42 chip. As a result, the non-coherent integration period must be at least 40 ms long, and the induced code delay for the autocorrelation peak must be at least 0.42. The autocorrelation function of the GPS C/A codes for various frequencies illustrated in Figure 37 is anticipated to have assistance from the Doppler code. Therefore, this defines the induced code delay and signal amplitude as obtained autocorrelation functions affected by the code Doppler obtained from the diverse Doppler frequencies of the numerous satellites in view.

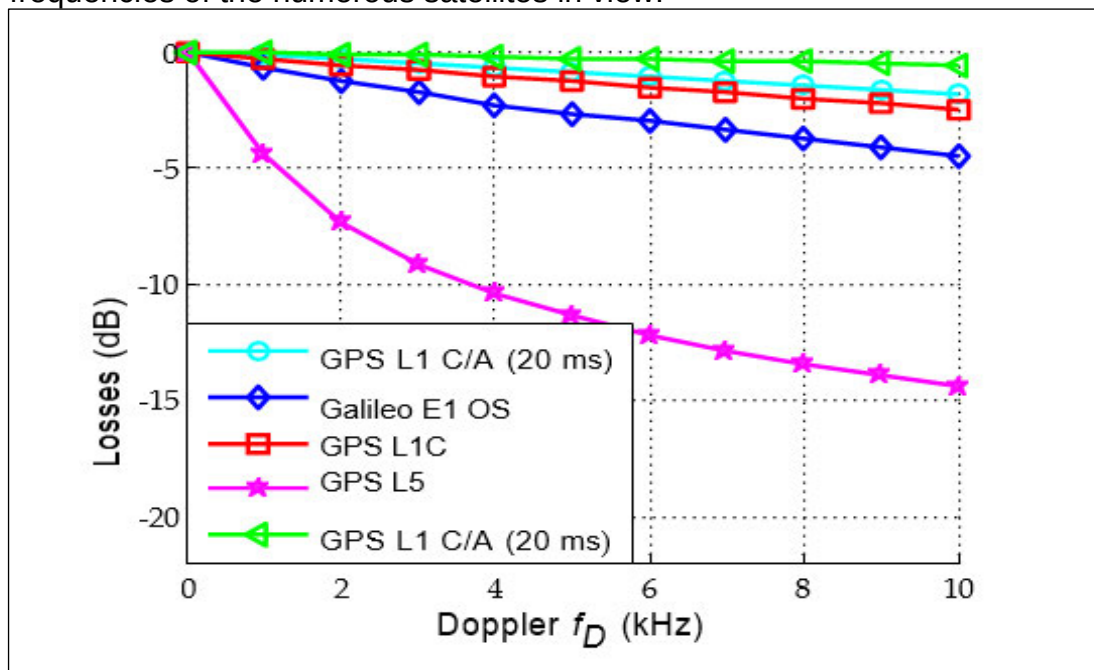


Figure 6.17: The GNSS signal Losses during autocorrelation because of the code Doppler changes.

For BOC-modulated signals, using the autocorrelation function, the signal is attenuated along the satellite path and the substantial shift of the code delay is identified.

As a result, increasing the Doppler frequency revealed issues with acquisition detection for several cells, which could lead to an instant failure. The solid orange lines in Figure 6.17 indicate the acquisition grid cell. Figure 6.17 illustrates the losses on the amplitude of the autocorrelation main peak, and these losses are affected by code Doppler. If the incoming Doppler frequency is high, there are chances of higher losses in the autocorrelation function. Figure 6.17 illustrates the losses in amplitude for modernized signals where the signal power varies between the satellites: the GPS L-1 C/A has about 2.5 dB, Galileo E1a has about 4.6 dB, and the GPS L-5 is approximately 15 dB. The acquisition modeling requirements of the BPSK modulated GPS signal require the scanning of approximately $4092/0.5 = 8184$ code phases along the search cells. While a similar spectral power Galileo E1a will necessitate a code length of $4092/0.17 = 24552$ code phases. The recent GNSS receivers are capable of multi-correlation, where the receiver is synchronized with the incoming GNSS signals, retrieving the navigation data to calculate the PVT solution and generate the GNSS observables or measurements. Recalling the equation from chapter three (3), equation (3.17) is the code replica for early, equation (3.18) is the code replica for late, and equation (3.19) is the code replica for prompt. There are some errors that can pass through the loop filter, and those errors are to be computed by the discriminator to recover the navigation message if it is corrupted. In Figures 6.18 and 6.19, the correlator outputs are illustrated for PRN17 of the GPS CA signal code.

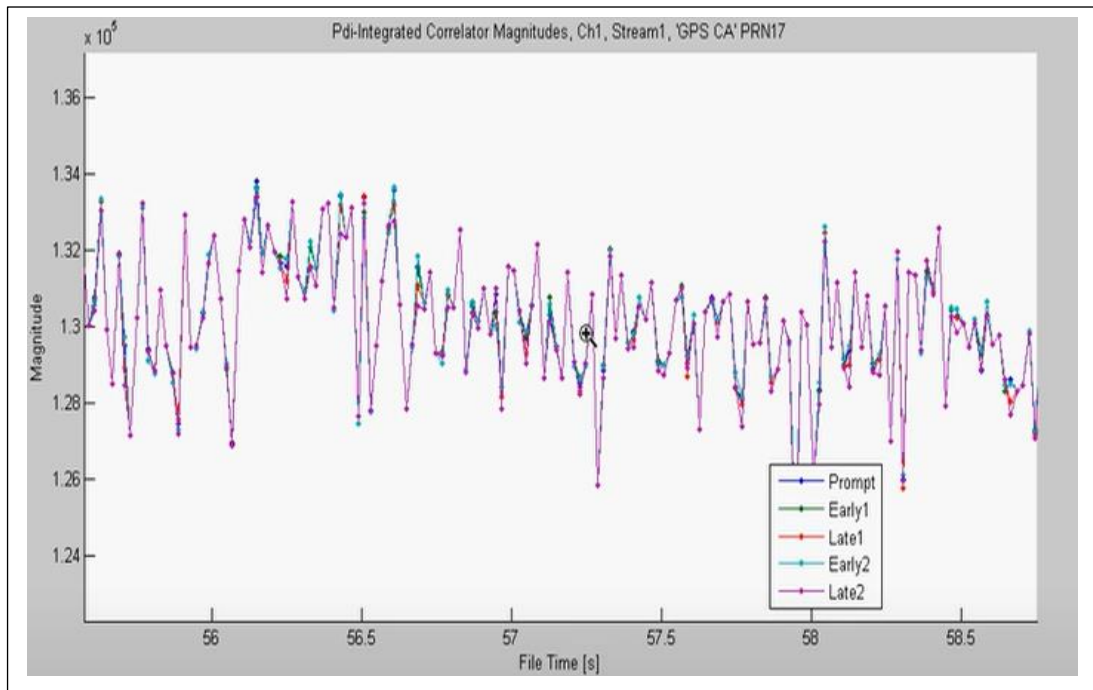


Figure 6.18: The illustration of the PDI integrated correlator magnitudes for GPS C/A code.

The integrated correlator magnitude for GPS CA in Figure 6.18 shows variable behaviour for all conditions due to its dependence on the nature and properties of the spreading code. It was further observed that, the spreading code is correlated to its self, since the integrated correlator magnitude varies between 1 and 2 as shown in Figure 6.18 and this called perfect alignment between the satellite and receiver in terms of elevation angle and satellite visibility. For misalignment, the correlator magnitude will be zero if the spreading code is self-correlated.

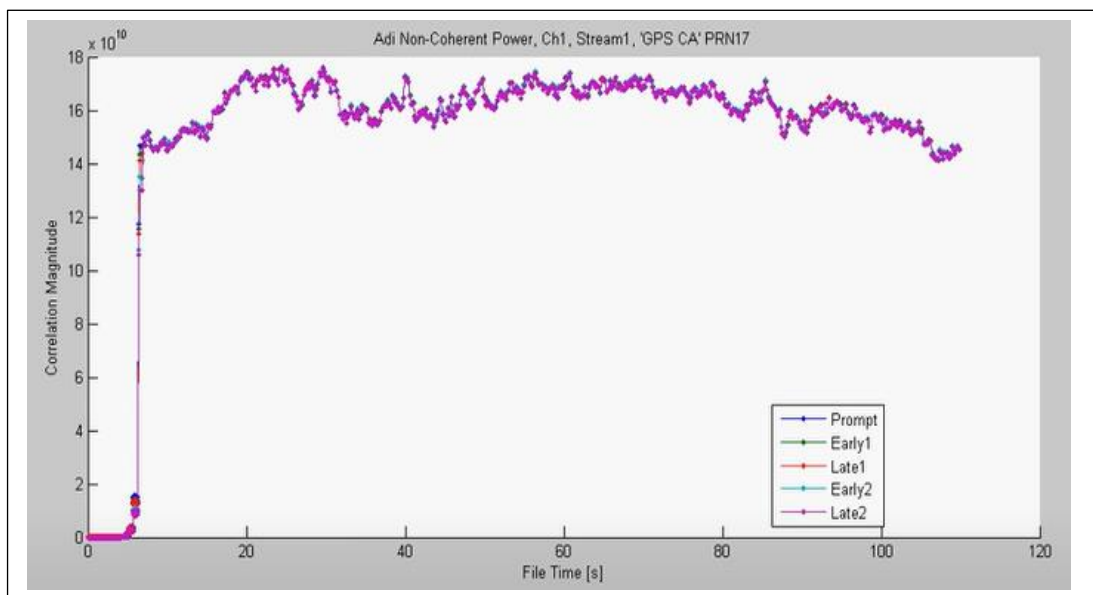


Figure 6.19: The illustration of the non-coherent power variations for GPS C/A.

In Figure 6.19, the ideal signal replicas have been used and the chip delays are 0.1, 0.2, 0.3, and 0.4. These chip delays are used for chip spacing to form the early and late correlation outcomes. In Figure 6.19, it was also observed that if the replica's correlation was without delay, the incoming signal would provide prompt results. In Figure 6.20, the C/N_0 ratio the GNSS receiver obstructed by the noise and multipath along the satellite path is illustrated.

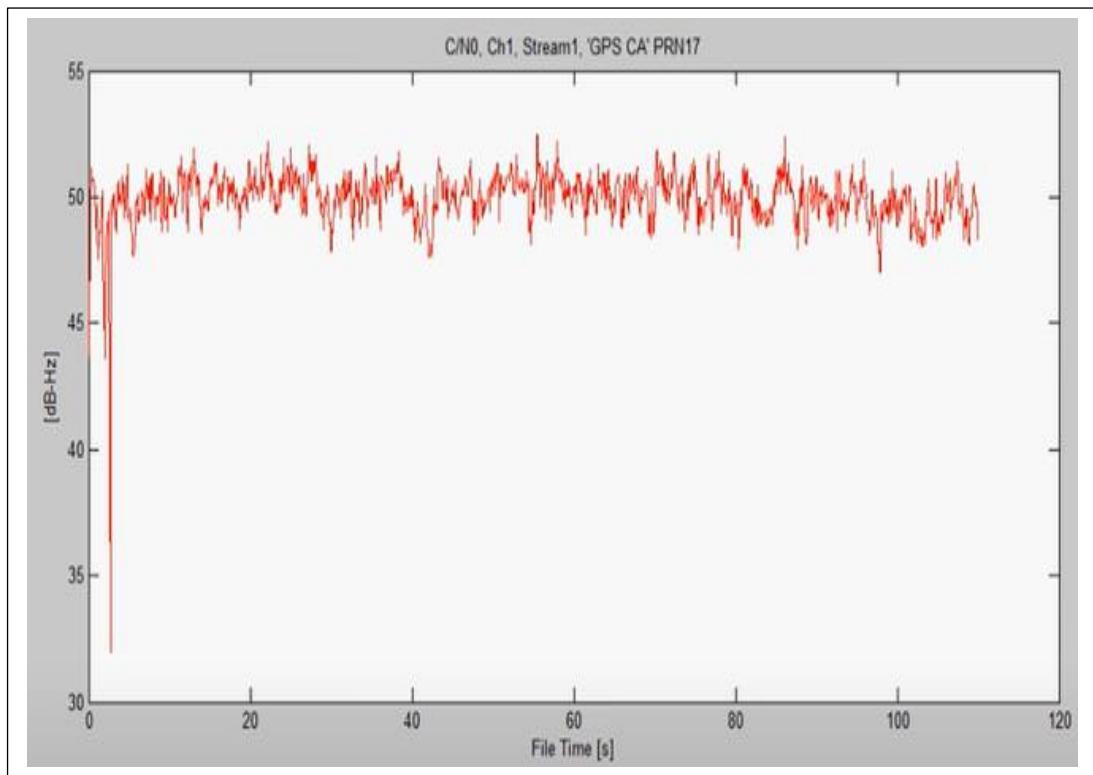


Figure 6.20 : The illustration of the C/N_0 GPS C/A code over the specific period.

The C/N_0 in Figure 6.20 is ranging between 50 dB Hz and 60 dB Hz, and the capabilities of the GNSS receiver used here make it possible to recover the navigation message if it is buried in the noise. This is the measure of the range between the satellite and the satellite and the impact of the noise in the signal carrier. Even though the satellite view is not very good and there are signal replicas, the concept of the CSD assisted the receiver in looking for alternative signals from space to improve the signal strength.

6.5. GNSS satellite availability

In this section, the satellite visibility is presented for GPS only and GPS plus Galileo, this static open sky analysis with live information as shown previously in chapter four (Figure 4.4 and 4.5): testing scenarios.

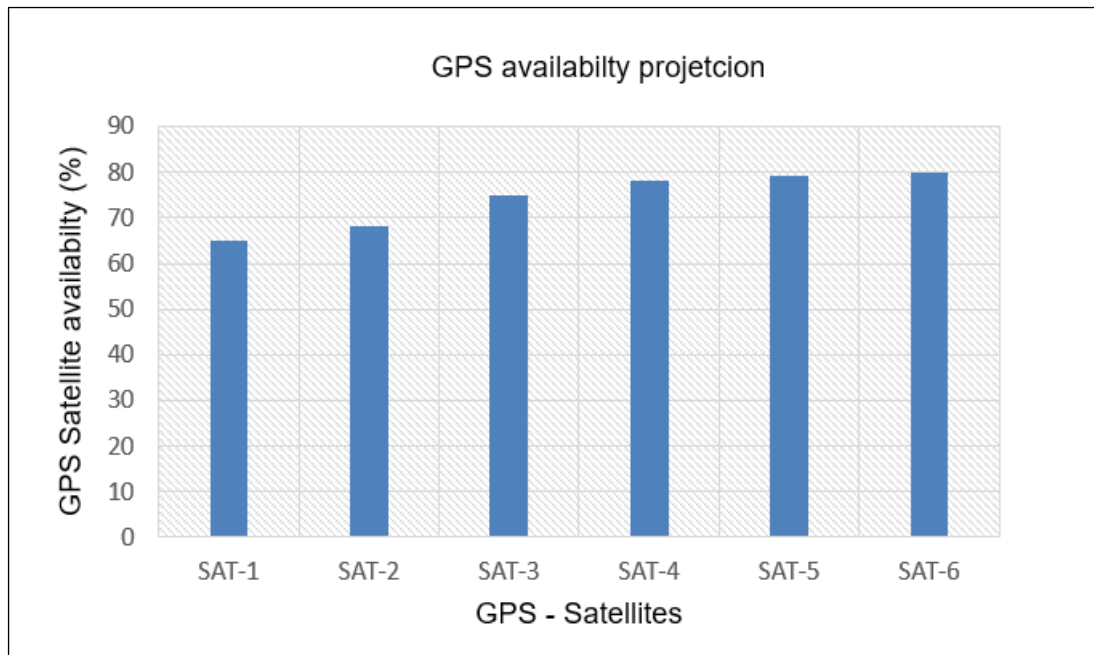


Figure 6.21 : The GPS satellites availability in the area with no obstruction. The location of the testing was selected in the manner to ensure that, atleast four satellite are visible from Galileo and GPS where the navigation data was calculated around 50 Hz frequency. In Figure 6.22 shows, an availability projection of the GPS satellite only and the receiver was in the best view.

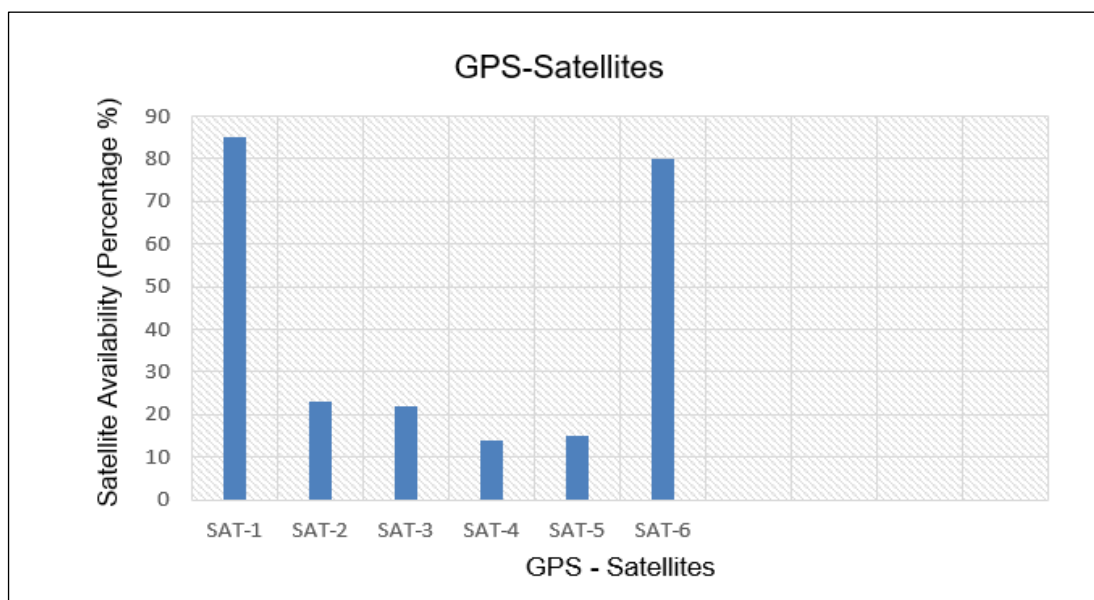


Figure 6.22: The GPS satellites visibility in the area with signal obstruction.

Without destruction, about six GPS satellites were at least 80% visible to the receiver. Hence, this is not an ideal situation since some of the receivers are dynamic. To cater for such conditions, the receiver location was changed to an area with only two GPS satellites that are 80% visible to the receiver. The other satellites were visible, but were only about 20% to 30% visible, and the weak signals from the poorly visible satellite introduced noise and other errors to the receiver. In the condition illustrated in Figure 6.22, it is not possible to obtain acceptable navigation data because the visibility and signal strength are poor. Hence, this condition is not ideal for GNSS applications; that is why the multi-signal GNSS receiver was then introduced in Figure 6.23.

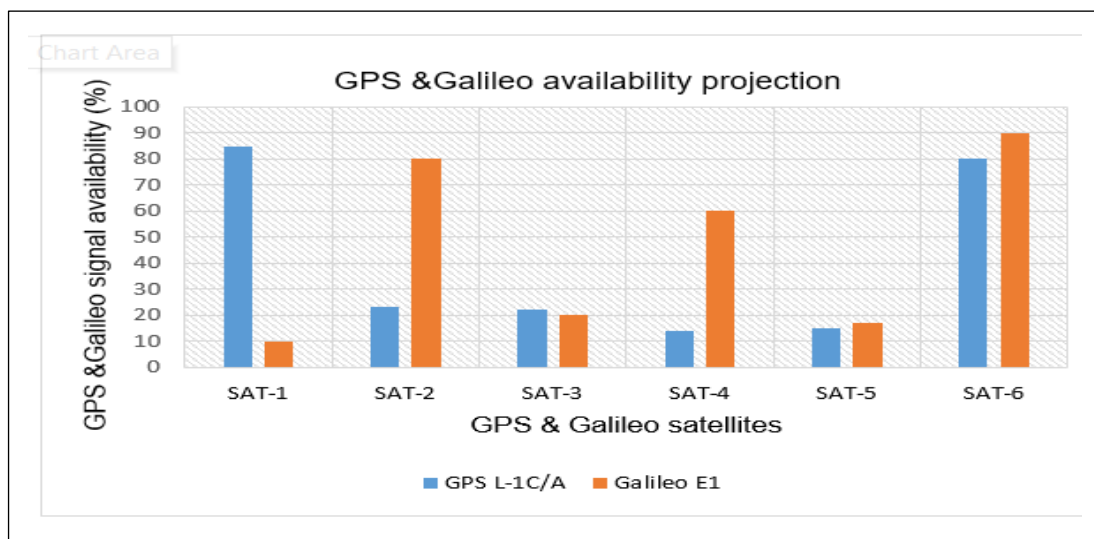


Figure 6.23: The GPS and Galileo satellites visibility in a location with maximum signal obstruction.

The same location of Figure 6.23 was retained, and the multi-signal processor was enabled so that the receiver will see other satellite constellations (the Galileo constellation). In Figure 6.23, there were two satellites that were adequately visible to the receiver; after enabling the multi-signal processor at the receiver, three more satellites for the Galileo constellation were visible, as shown in Figure 6.24. Hence, the GNSS receiver was now exposed to five satellites to process and calculate navigation data. This is the main objective of this research work: to improve the satellite visibility and signal strength in challenging locations by adopting the concept of CSD, which requires the use of a multi-signal GNSS receiver. In Figure 6.23, the satellite visibility and signal strength have been improved. Hence, this condition is ideal for all GNSS applications, more so in the case of dynamic GNSS receivers.

6.7. Summary and conclusions

The purpose of GNSS is to calculate the position, velocity, and time. Accuracy and reliability are mandatory in all GNSS applications. Reliability means the improved availability of GNSS satellites, good signal strength, reduced signal losses, attenuation, interference, diffraction, and multipath along the satellite path. Hence, this chapter investigated the performance of the CSD using the GNSS receivers that are capable of multi-signal processing. This comes after the CSD has been introduced and implemented in Chapter 4, and investigating the sources of the signal acquisition degradation on GNSS receivers in Chapter 5. It was observed that there are five factors that can influence the reliability and accessibility of the GNSS satellites:

- The satellite geometry
- Signal multipath
- Atmospheric delays
- Clock errors
- Ephemeris errors

Regarding the satellite geometry issues, there is not much that can be done to resolve any issues relating to the hardware failure and physical geometry of the GNSS satellites. The adoption of the CSD methodology can resolve the factors listed above, because if one satellite has a hardware failure or is generating an evil waveform, it can be ignored and the receiver will continue to search for the visible and healthy satellite. The GNSS receivers used here are capable of cross-correlating the signals from the different constellations. However, the interest of this research work was the relationship between the GPS and Galileo constellations. Furthermore, consideration must be given to possible variations in the Doppler shift and the continuous integration of the Doppler shift. Regarding the changes and the integration in the Doppler shift, there are two types of GNSS receivers: stationary and mobile receivers. The Doppler shift is expected to change differently between these receivers depending on their location and design specifications.

If the GNSS satellite is at its maximum range, the received GNSS signals are likely to reach the maximum Doppler shift that ranges from $+41/2$ to 6 cycles per millisecond. This is predictable, due to the constant changes in the Doppler shift of the signal. Therefore, the receiver oscillator frequency must be synchronized to match the changes of the incoming waveform or signal. The Doppler shift and the phase carrier of the incoming GNSS signal are measured through the combination of the receiver oscillation frequency and the frequency of the received signal. The oscillator frequency is constant and generated by the receiver. From the observation and discussions from chapters four to six, it was concluded that the adoption of the CSD could improve the reliability of the GNSS and further meet the demands of the GNSS applications in terms of PVT. Furthermore, the CSD requires the use of a multi-signal GNSS receiver. Chapters four to six were devoted to the improvement of the GNSS' reliability.

CHAPTERS SEVEN

Conclusion and Future Work

7.1. Background

Recently, the GNSS has been used in many fields and applications such as sport, leisure, transportation (railways, aviation, road, or water), electrical industries, agriculture, and banking. The availability of the GNSS signal improved as from the year of 2019 due to the introduction of the Beidou and Galileo, and it has implied the redesign of the GNSS receivers globally. The modern GNSS signals are different from the old signals, and the old systems like GPS were improved to match the requirements of the GNSS applications. In many areas of the world, including South Africa, GPS is still used. The acquisition of the signal plays a crucial role in GNSS receiver configurations. In this research work, the broad study of the GNSS receiver and acquisition methodologies for legacy and modernized signals are discussed, along with signal tracking. The layout of this thesis was based on achieving the objectives and goals of this thesis and further encourage the adoption of the CSD in GNSS receivers. The simulations, results and analysis presented in this research conform to the thesis objectives and goals. The performance of the multi-constellation GNSS receivers in dual mode operation (GPS and Galileo) was compressively investigated to prove that, the research objectives has been met. The practical work carried out proved the effectiveness of the proposed solution (CSD).

7.2. Chapters synopses

Chapter one: Referring to Chapter 1, the purpose of this research work was to study the GNSS signal degradation, with a high focus on the multipath signals, and further investigate the methodology of mitigating the multipath signals. Chapter one briefly describes the background of the GNSS signal propagation channels and introduces the sources of the signal degradation in GNSS applications, as illustrated in Figure 1.1. Furthermore, the power losses for indoor GNSS applications are defined and presented in Figure 1.2. The objectives and goals for this research are defined in chapter one.

The innovative method was proposed in chapter four, the CSD, and it was further expanded, analysed, and discussed in chapters five and six. To reach the objectives of this research, it was required to evaluate and analyse the main source of the signal degradation and attenuation along the satellite path, which in this case was GNSS signal multipath. The design of the recent GNSS signal is different, as is the modulation scheme.

Chapter two: The second chapter of this research work presented the state of the art of GNSS constellations as well as the design of GNSS receivers. Chapter two is a broad and detailed chapter that articulates the architecture of the GNSS. The GNSS signal, propagation, processing, acquisition, tracking, and modulation are presented in chapter two to provide the reader with insight into what is happening to the GNSS receivers. The recent GNSS signals are made up of two components: the data and pilot components. The data component is the one that carries the navigation information, and the pilot is dateless for both GPS and Galileo. The pilot is used for robust signal tracking along the processing stages in the GNSS receiver. Looking at the structure of the pilot components, it is similar to the data component. However, the data component contains the spreading code that is different from the spreading code of the pilot component. The secondary code of the data component specifies that the code bit must only last for one PRN code of repetition. Hence, the splitting of the received signals into two components means the total signal power is also divided by 50% for each component. On the other hand, the GPS L1C has about a 75% share of the power on the pilot component, meaning the GPS L1C does not divide equally.

Chapter three: Moving on to Chapter 3, the GNSS multipath was described in detail, including all possible types. The GNSS signal multipath is defined as the scene of the signal reflection for the received signal, and the objects nearby the GNSS receiver cause this. The GNSS signal multipath is largely experienced in areas with long buildings and trees, and sometimes the configuration files are uploaded to the GNSS receiver. In this case, two signals reach the GNSS receiver. Furthermore, the impact of the signal multipath on the GNSS code pseudorange measurement is discussed here.

Chapter four: In chapter four, the CSD is proposed, implemented, and discussed comprehensively. The architecture of signal collection is provided in Figure 4.3 for different locations to elaborate the concept of signal collection in different environments. The recent GNSS receivers are capable of multiple frequencies; hence, the CSD was proposed to the GNSS receivers to receive and process signals from two constellations, Galileo and GPS. Because there are obvious similarities between the Galileo E5a and the GPS L5, this is used to address GNSS signal multipath issues at the user level. This research work was only interested in GPS and Galileo signals.

Chapter five: The investigation of other sources that contribute to signal degradation was presented in Chapter 5 of this work. Apart from the GNSS signal multipath, there are other sources that contribute largely to the signal attenuation along the satellite channels. Most of the sources of the signal degradation discussed in Chapter 5 can be resolved using differential methods that are not similar to the CSD. The sources of the signal degradation here in chapter five correspond to the sources illustrated in chapter one figure 1.1.

Chapter Six: In Chapter Six, the performance of the CSD is evaluated and compared to that of ordinary signal detection. The results demonstrated that, when a multi-frequency GNSS receiver is used, CSD can be implemented and signal multipath is addressed in accordance with satellite availability.

7.3. The Future Work are Summarized as Follows.

In line with the results of this research work, numerous questions are being raised for GNSS applications, which implies the need for continuous investigations.

- The detailed analysis of the SBAS: These systems are implemented to augment the GNSS regionally to improve its integrity and precision. The old GPS and Glonass systems were not capable of real-time data functions. The concern is that the African SBAS is not comprehensively discussed and no further data is being provided at this time. There is a strong need for further investigation here to improve the reliability of the African systems.
- The effect of bit-sign transitions on coherent integration times: In chapter five, the probability of detection is briefly studied and analysed, and there

are assumptions that were made to carry out such studies. The assumption is that only one bit-sign transition can occur over the period of signal correlation, depending on the type of correlation.

In the case of GPS L1 C/A signals, the integration times are the dividers of the data bit duration. Hence, this can be further studied for coherent integration times ranging between 3 to 7 ms for GPS L1 C/A signal links.

- Improving GNSS signal tracking strategies: The recent GNSS receiver had a heavy load processing signals from different satellites. There are two main steps here: the acquisition and tracking. The provided acquisition is satellite-based, and the pseudorange measurements in the case of multi-constellation are not similar and need proper processing for accurate data. The improved tracking strategies should be developed and aligned for multi-frequency GNSS receivers. The fact is, the signals from the recent GNSS constellation cannot be tracked using the same method as traditional signals like GPS L1 C/A. Hence, the innovative tracking method needs to be developed to fully utilize the capabilities of the new GNSS signals.
- Investigate more methodologies for mitigating signal attenuation and multipath for indoor GNSS applications: In Figure 1.2, the GNSS power losses of the indoor application are illustrated, and there is a huge power loss to the signal for concrete walls and roofing. Hence, alternative methodologies to deal with these losses must be investigated to improve the reliability of the indoor GNSS. For example, in the electrical industry, where protection relays and remote terminal units are installed indoors in many cases, accurate time synchronization for real-time data monitoring is mandatory. Therefore, there is a strong need to investigate new models and design a receiver that will be more sensitive to the received signals.
- Study the de-correlation of the multipath components in subspace systems: The incoming signals of the GPS L-1 and GPS L-2 are propagated through similar wireless channels under different conditions emitted by the one satellite, and they reach the same receiver with a minimum time difference in terms of their arrival. Hence, these two GPS signals can be used as two branches to diversify the frequencies and enhance the de-correlation of the multipath component.

References

- [1] C. J. Hegarty and E. Chatre, "Evolution of the global navigation satellitesystem (gnss)," *The Proceedings of the IEEE*, vol. 96, no. 12, pp. 1902-1917, 2008.
- [2] E. M. Alessi , A Rossi, GB Valsecchi and L Anselmo ., "Effectiveness of GNSS disposal strategies," *Acta Astronautica*, vol. 99, pp. 292-302, 2014.
- [3] C. D. Bussy-Virat, C. S. Ruf, and A. J. Ridley, "Relationship between temporal and spatial resolution for a constellation of GNSS-R satellites," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 12, no. 1, pp. 16-25, 2018.
- [4] P. F. Silva, H.D. Lopes, T.R. Peres, J.S. Silva and J. Ospina "Weak GNSS signal navigation to the moon," 26th *Proceedings of International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2013)*, pp. 3357-3367, 2013.
- [5] V. Capuano, A. Harvard, and S.-J. Chung, "On-board cooperative spacecraft relative navigation fusing GNSS with vision," *Progress in Aerospace Sciences*, vol. 128, p. 100761, 2022.
- [6] J. Kiessling, "Robust Navigation Issue in the Event of GNSS Failures," 2013.
- [7] R. M. Ferre., "Is LEO-Based Positioning with Mega-Constellations the Answer for Future Equal Access Localization?," *IEEE Communications Magazine*, vol. 60, no. 6, pp. 40-46, 2022.
- [8] G. MacGougan, G. Lachapelle, R. Nayak, and A. Wang, "Overview of GNSS signal degradation phenomena," in *Proceedings of the International Symposium Kinematic Systems and Geodesy, Geomatics and Navigation*, 2001.
- [9] M. Unwin, P. Jales, P. Blunt, and S. Duncan, "Preparation for the first flight of SSTL's next generation space GNSS receivers," 6th *ESA Workshop on Satellite Navigation Technologies (Navitec) & European*

Workshop on GNSS Signals and Signal Processing, Netherlands, pp. 1-6, 2012.

- [10] B. Hofmann-Wellenhof, H. Lichtenegger, and E. Wasle, GNSS—global navigation satellite systems: GPS, GLONASS, Galileo, and more. Springer Science & Business Media, 2007.
- [11] J. Wang, C. Rizos, M. P. Stewart, and A. Leick, "GPS and GLONASS integration: modeling and ambiguity resolution issues," *GPS solutions*, vol. 5, no. 1, pp. 55-64, 2001.
- [12] G. Johnston, A. Riddell, and G. Hausler, "The international GNSS service," Springer handbook of global navigation satellite systems: Springer, pp. 967-982, 2017.
- [13] E. D. Kaplan and C. Hegarty, Understanding GPS/GNSS: Principles and applications. Artech house, 2017.
- [14] C. J. Hegarty, "GNSS signals—An overview," International Frequency Control Symposium Proceedings, 2012, pp. 1-7, 2012.
- [15] S. Kumar and K. B. Moore, "The evolution of global positioning system (GPS) technology," Journal of science Education and Technology, vol. 11, no. 1, pp. 59-80, 2002.
- [16] H. Tsuji ., "Modernization of GEONET from GPS to GNSS," Bulletin of the Geospatial Information Authority of Japan, vol. 61, no. 12, pp. 9-20, 2013.
- [17] R. Alkan, H. Karaman, and M. Sahin, "GPS, GALILEO and GLONASS satellite navigation systems & GPS modernization," Proceedings of 2nd International Conference on Recent Advances in Space Technologies, 2005. RAST 2005., 2005, pp. 390-394, France, 2005.
- [18] B. Eissfeller, C. Tiberius, T. Pany, R. Biberger, and G. Heinrichs, "Real-time kinematic in the light of GPS modernization and Galileo," Proceedings of the 14th International Technical Meeting of the Satellite Division of The Institute of Navigation, pp. 650-682, Germany, 2001.
- [19] B. Eissfeller, C. Tiberius, T. Pany, R. Biberger, T. Schueler, and G. Heinrichs, "Instantaneous ambiguity resolution for GPS/Galileo RTK positioning," Proceedings of the 9th Saint Petersburg International Conference on Integrated Navigation Systems, Russia, pp. 27-29, 2002.

- [20] K. Agarwal and A. Alphones, "Triple-band compact circularly polarised stacked microstrip antenna over reactive impedance meta-surface for GPS applications," *IET microwaves, antennas & propagation*, vol. 8, no. 13, pp. 1057-1065, 2014.
- [21] S. Thaelert, P. Steigenberger, O. Montenbruck, and M. Meurer, "Signal analysis of the first GPS III satellite," *GPS Solutions*, vol. 23, no. 4, pp. 1-11, 2019.
- [22] B. R. Rao, K. McDonald, and W. Kunysz, *GPS/GNSS Antennas*. Artech House, 2013.
- [23] Y. Urlichich, V. Subbotin, G. Stupak, V. Dvorkin, A. Povalyaev, and S. Karutin, "GLONASS modernization," Proceedings of the 24th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2011), Russia, pp. 3125-3128, 2011.
- [24] S. Choy, J. Kuckartz, A. G. Dempster, C. Rizos, and M. Higgins, "GNSS satellite-based augmentation systems for Australia," *GPS solutions*, vol. 21, no. 3, pp. 835-848, 2017.
- [25] U. U. Hussine, Y. Huang, and C. Song, "A new circularly polarized antenna for GNSS applications," 11th European Conference on Antennas and Propagation (EUCAP), France, pp. 1954-1956, 2017.
- [26] M. van der Meijde, R. Pail, R. Bingham, and R. Floberghagen, "GOCE data, models, and applications: A review," *International Journal of Applied Earth Observation and Geoinformation*, vol. 35, pp. 4-15, 2015.
- [27] S. A. Younes, "Application of Digital Model of Meteorological Data in Tropospheric Delay Errors estimation of GNSS Measurements," 2022.
- [28] A. Şmuleac, I. Nemeş, I. A. Creţan, N. S. Nemeş, and L. Şmuleac, "Comparative Study of the Volumetric Methods Calculation Using GNSS Measurements," *IOP Conference Series: Materials Science and Engineering*, vol. 245, no. 5, p. 052020, 2017.
- [29] S. Jin, G. Occhipinti, and R. Jin, "GNSS ionospheric seismology: Recent observation evidences and characteristics," *Earth-Science Reviews*, vol. 147, pp. 54-64, 2015.

- [30] S. Banville and R. B. Langley, "Mitigating the impact of ionospheric cycle slips in GNSS observations," *Journal of Geodesy*, vol. 87, no. 2, pp. 179-193, 2013.
- [31] J. S. Subirana, M. Hernandez-Pajares, and J. e. M. J. Zornoza, *GNSS Data Processing: Fundamentals and Algorithms*. European Space Agency, 2013.
- [32] L. Lau and P. Cross, "Development and testing of a new ray-tracing approach to GNSS carrier-phase multipath modelling," *Journal of Geodesy*, vol. 81, no. 11, pp. 713-732, 2007.
- [33] J. Geng and G. Li, "On the feasibility of resolving Android GNSS carrier-phase ambiguities," *Journal of Geodesy*, vol. 93, no. 12, pp. 2621-2635, 2019.
- [34] P. D. Groves, L. Wang, and M. Ziebart, "Shadow matching: Improved GNSS accuracy in urban canyons," *GPS World*, vol. 23, no. 2, pp. 14-18, 2012.
- [35] G. Petit, "Sub-10–16 accuracy GNSS frequency transfer with IPPP," *GPS Solutions*, vol. 25, no. 1, pp. 1-9, 2021.
- [36] S. S. Vemuri and B. Dappuri, "Walker-Delta Constellation Design for LEO-based Navigation using small satellites," 2022.
- [37] D. Kong, *Civil liability for damage caused by global navigation satellite system*. Kluwer Law International BV, 2019.
- [38] P. A. Iannucci and T. E. Humphreys, "Economical fused leo gnss," in *2020 IEEE/ION Position, Location and Navigation Symposium (PLANS)*, USA, 2020, pp. 426-443, 2020.
- [39] J. M. Kelner, C. Ziółkowski, L. Nowosielski, and M. Wnuk, "Reserve navigation system for ships based on coastal radio beacons," *The IEEE/ION Position, Location and Navigation Symposium (PLANS)*, USA, 2016, pp. 393-402, 2016.
- [40] J. Yuan, W. Yan, S. Li, and Y. Hua, "Demodulation method for Loran-C at low SNR based on envelope correlation–phase detection," *Sensors*, vol. 20, no. 16, p. 4535, 2020.
- [41] W. Yan, K. Zhao, S. Li, X. Wang, and Y. Hua, "Precise Loran-C signal acquisition based on envelope delay correlation method," *Sensors*, vol. 20, no. 8, p. 2329, 2020.

- [42] R. Yozevitch, B. B. Moshe, and A. Weissman, "A robust GNSS los/nlos signal classifier," *Navigation: Journal of The Institute of Navigation*, vol. 63, no. 4, pp. 429-442, 2016.
- [43] N. Zhu, J. Marais, D. Bétaille, and M. Berbineau, "GNSS position integrity in urban environments: A review of literature," *IEEE Transactions on Intelligent Transportation Systems*, vol. 19, no. 9, pp. 2762-2778, 2018.
- [44] S. Hewitson and J. Wang, "GNSS receiver autonomous integrity monitoring (RAIM) performance analysis," *Gps Solutions*, vol. 10, no. 3, pp. 155-170, 2006.
- [45] Q. Zhang , "A refined metric for multi-GNSS constellation availability assessment in polar regions," *Advances in Space Research*, vol. 66, no. 3, pp. 655-670, 2020.
- [46] G. M. Fu, M. Khider, and F. van Diggelen, "Android Raw GNSS measurement datasets for precise positioning," *Proceedings of the 33rd international technical meeting of the satellite division of the Institute of Navigation (ION GNSS)*, pp. 1925-1937, 2020.
- [47] P. Catania et al., "Positioning accuracy comparison of GNSS receivers used for mapping and guidance of agricultural machines," *Agronomy*, vol. 10, no. 7, p. 924, 2020.
- [48] F. Engel, G. Heiser, P. Mumford, K. Parkinson, and C. Rizos, "An open GNSS receiver platform architecture," in *The 2004 International Symposium on GPS/GNSS, 2004: School of Surveying and Spatial Information Systems, UNSA*.
- [49] S. Jin, E. Cardellach, and F. Xie, *GNSS remote sensing*. Springer, 2014.
- [50] Y. J. Morton, F. van Diggelen, J. J. Spilker Jr, B. W. Parkinson, S. Lo, and G. Gao, *Position, navigation, and timing technologies in the 21st century: Integrated satellite navigation, sensor systems, and civil applications, volume 1*. John Wiley & Sons, 2021.
- [51] Y. Xu, Q. Chang, and Z. Yu, "On new measurement and communication techniques of GNSS inter-satellite links," *Science China Technological Sciences*, vol. 55, no. 1, pp. 285-294, 2012.

- [52] M. Wang, X. Lu, and Y. Rao, "GNSS Signal Distortion Estimation: A Comparative Analysis of L5 Signal from GPS II and GPS III," *Applied Sciences*, vol. 12, no. 8, p. 3791, 2022.
- [53] B. Anyaegbunam, "Design elements of satellite telemetry, tracking and control subsystems for the proposed Nigerian made satellite," *Int. J. Eng. Sci. Invention*, vol. 3, no. 1, pp. 5-13, 2014.
- [54] E. Turan, S. Speretta, and E. Gill, "Autonomous navigation for deep space small satellites: Scientific and technological advances," *Acta Astronautica*, 2022.
- [55] M. N. Dazhi, H. Al-Hraishawi, M. R. B. Shankar, and S. Chatzinotas, "Uplink capacity optimization for high throughput satellites using sdn and multi-orbital dual connectivity," *The International Conference on Communications Workshops (ICC Workshops)*, Korea, 2022, pp. 544-549, 2022.
- [56] Q. Chen, Z. Wang, G. F. Pedersen, and M. Shen, "Joint Satellite-Transmitter and Ground-Receiver Digital Pre-Distortion for Active Phased Arrays in LEO Satellite Communications," *Remote Sensing*, vol. 14, no. 17, p. 4319, 2022.
- [57] B. C. Fredrick, "Geolocation of source interference from a single satellite with multiple antennas," *NAVAL POSTGRADUATE SCHOOL MONTEREY CA* 2014.
- [58] L. You , "Hybrid analog/digital precoding for downlink massive MIMO LEO satellite communications," *Transactions on Wireless Communications*, 2022.
- [59] H. Hurskainen, J. Raasakka, T. Ahonen, and J. Nurmi, "Multicore software-defined radio architecture for GNSS receiver signal processing," *EURASIP Journal on Embedded Systems*, vol. 2009, pp. 1-10, 2009.
- [60] F. Pereira and D. Selva, "Tradespace analysis of GNSS space segment architectures," *Transactions on Aerospace and Electronic Systems*, vol. 57, no. 1, pp. 155-174, 2020.
- [61] S. Dawoud, "GNSS principles and comparison," *Potsdam University*, 2012.

- [62] M. Hernandez-Pajares, "The ESA/UPC GNSS-Lab tool (gLAB): An advanced multipurpose package for GNSS data processing," 5th ESA Workshop on Satellite Navigation Technologies and European Workshop on GNSS Signals and Signal Processing (NAVITEC), Noordwijk, pp. 1-8, 2010.
- [63] P. Korba and J. Sabo, "Aviation applications for user segment," NAŠE MORE: znanstveni časopis za more i pomorstvo, vol. 61, no. 1-2, pp. S13-17, 2014.
- [64] B. Madonsela, I. Davidson, and C. Mulangu, "The Analysis of Global Navigation Satellite Systems (GNSS) and the Numerical Estimation of Multipath Propagation," The 1st International Conference on Maritime Education and Development, pp. 411-425, 2021: Springer.
- [65] L. J. Schaub, "GPS Control Segment," AIR FORCE SPACE COMMAND LOS ANGELES AFB CA SPACE AND MISSILE SYSTEMS CENTER, 2015.
- [66] W. Bollwerk, "The Alternate Master Clock and Precise Time Requirements; Why an Alternate Master Clock?," in Proceedings of the 28th Annual Precise Time and Time Interval Systems and Applications Meeting, 1996, pp. 141-150.
- [67] J.-M. Baracco, L. Salghetti-Drioli, and P. de Maagt, "AMC low profile wideband reference antenna for GPS and GALILEO systems," Transactions on Antennas and Propagation, vol. 56, no. 8, pp. 2540-2547, 2008.
- [68] J. Walker and J. Awange, "Global navigation satellite system," in Surveying for Civil and Mine Engineers: Springer, 2020, pp. 281-294.
- [69] T. Logsdon, "The navstar GPS," in Understanding the Navstar: Springer, 1995, pp. 17-33.
- [70] M. E. Ali, "Global Positioning System (GPS): Definition, Principles, Errors, Applications & DGPS," no. April, 2020.
- [71] P. Raju, "Fundamentals of GPS," Satellite Remote Sensing and GIS Applications in Agricultural Meteorology, vol. 121, 2003.

- [72] J. Benedicto, S. Dinwiddy, G. Gatti, R. Lucas, and M. Lugert, "GALILEO: Satellite system design," in European Space Agency: Citeseer, 2000.
- [73] J. P. Bartolomé, X. Maufroid, I. F. Hernández, J. A. López Salcedo, and G. S. Granados, "Overview of Galileo system," The GALILEO Positioning Technology: Springer, 2015, pp. 9-33, 2015.
- [74] J. Nurmi, E. S. Lohan, S. Sand, and H. Hurskainen, GALILEO positioning technology. Springer, 2015.
- [75] G. Galluzzo , "Galileo system status, performance metrics and results," The Proceedings of the International Technical Meeting of The Institute of Navigation, pp. 790-809,2018.
- [76] T. Weber, H. L. Trautenberg, and C. Schafer, "GALILEO System Architecture-Status and Concepts," The Proceedings of the 14th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS), pp. 1264-1272,2021.
- [77] P. Buist, A. Mozo, and H. Tork, "Overview of the Galileo Reference Centre: Mission, Architecture and Operational Concept," The Proceedings of the 30th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS), pp. 1485-1495,2017.
- [78] H. Blomenhofer, W. Ehret, A. Leonard, and E. Blomenhofer, "GNSS/Galileo global and regional integrity performance analysis," Te Proceedings of the 17th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS), pp. 2158-2168,2004.
- [79] J.-A. Avila-Rodriguez, S. Wallner, G. W. Hein, B. Eissfeller, M. Irsigler, and J.-L. Issler, "A vision on new frequencies, signals and concepts for future GNSS systems," The Proceedings of the 20th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS), pp. 517-534,2007.
- [80] C. Rizos, "Multi-constellation GNSS/RNSS from the perspective of high accuracy users in Australia," Journal of spatial science, vol. 53, no. 2, pp. 29-63, 2008.

- [81] L. Guo, F. Wang, J. Sang, X. Lin, X. Gong, and W. Zhang, "Characteristics analysis of raw multi-GNSS measurement from Xiaomi Mi 8 and positioning performance improvement with L5/E5 frequency in an urban environment," *Remote Sensing*, vol. 12, no. 4, p. 744, 2020.
- [82] C. S. Carrano, K. M. Groves, W. J. McNeil, and P. H. Doherty, "Scintillation characteristics across the GPS frequency band," *The Proceedings of the 25th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS)*, pp. 1972-1989, 2012.
- [83] X. Pi, B. A. Iijima, and W. Lu, "Effects of ionospheric scintillation on GNSS-based positioning," *Navigation: Journal of The Institute of Navigation*, vol. 64, no. 1, pp. 3-22, 2017.
- [84] Z. A. Khezzar, R. Benzid, L. Saidi, and M. K. Smail, "Envelope Detection by Shannon Energy Calculation in DCT Domain and DFS-Based Notch Filter for Interference Mitigation in GNSS Receivers," *Traitement du Signal*, vol. 39, no. 3, 2022.
- [85] S. Jin, Q. Wang, and G. Dardanelli, "A Review on Multi-GNSS for Earth Observation and Emerging Applications," *Remote Sensing*, vol. 14, no. 16, p. 3930, 2022.
- [86] T. S. Rappaport, *Wireless communications: principles and practice*. prentice hall PTR New Jersey, 1996.
- [87] A. Lehner and A. Steingaß, "Measuring the Navigation Multipath Channel: A Statistical Analysis," *ION GNSS*, 2004.
- [88] A. J. Viterbi, *CDMA: principles of spread spectrum communication*. Addison Wesley Longman Publishing Co., Inc., 1995.
- [89] Z. Zhang and L. Pan, "Current performance of open position service with almost fully deployed multi-GNSS constellations: GPS, GLONASS, Galileo, BDS-2, and BDS-3," *Advances in Space Research*, vol. 69, no. 5, pp. 1994-2019, 2022.
- [90] B. Motella, M. Nicola, and S. Damy, "Enhanced GNSS authentication based on the joint CHIMERA/OSNMA scheme," *IEEE Access*, vol. 9, pp. 121570-121582, 2021.
- [91] K. Yu, *Theory and practice of GNSS reflectometry*. Springer, 2021.

- [92] M. Yuan, X. Tang, S. Lou, C. Ma, and G. Ou, "Cross-Correlation Based Spreading Code Authentication Scheme for Civil GNSS Signals," in China Satellite Navigation Conference, 2022, pp. 503-514: Springer.
- [93] Z. Yao and M. Lu, Next-Generation GNSS Signal Design. Springer, 2021.
- [94] A. Kumar, S. Kumar, P. Lal, P. Saikia, P. K. Srivastava, and G. P. Petropoulos, "Introduction to GPS/GNSS technology," in GPS and GNSS technology in geosciences: Elsevier, pp. 3-20, 2021.
- [95] J. Machaj, P. Brida, N. Majer, and R. Ščehovič, "Impact of GPS Interference on Time Synchronization of DVB-T Transmitters," Mobile Information Systems, vol. 2021, 2021.
- [96] J. Ha, K.-D. Park, and H.-I. Kim, "Avaliable analysis of precise positioning using the LX-PPS GNSS permanent stations," Journal of Cadastre & Land InformatiX, vol. 51, no. 1, pp. 23-38, 2021.
- [97] Y. Guo et al., "Method for Estimating the Optimal Coefficient of L1C/B1C Signal Correlator Joint Receiving," Remote Sensing, vol. 14, no. 6, p. 1401, 2022.
- [98] S. C. Fisher and K. Ghassemi, "GPS IIF-the next generation," Proceedings of the IEEE, vol. 87, no. 1, pp. 24-47, 1999.
- [99] J. Sanz, J. Juan, and M. Hernández-Pajares, "GNSS Data Processing, Vol. I: Fundamentals and Algorithms. Noordwijk, the Netherlands: ESA Communications," ESTEC TM-23/1, 2013.[Online]. Available: [http://www.navipedia.net/GNSS ...2013](http://www.navipedia.net/GNSS...2013).
- [100] C. A Ogaja, "GNSS Constellations and Signals," in Introduction to GNSS Geodesy: Springer, pp. 13-19, 2022.
- [101] X. Luo, L. You, J. Lv, and C. Zhong, "Multidomain Narrowband Interference Intelligent Suppression Method Based on Cognitive Radio and MIMO in UAV Data Link," Computational Intelligence and Neuroscience, vol. 2022, 2022.
- [102] A. Romani, F. Bigongiari, and L. Fanucci, "Feasibility Study of a Unified Fast Acquisition Core for Modern GPS Signals," in International Conference on Applications in Electronics Pervading Industry, Environment and Society, pp. 200-205, 2022: Springer.

- [103] J. Starzyk and Z. Zhu, "Averaging correlation for C/A code acquisition and tracking in frequency domain," *Proceedings of the 44th The Midwest Symposium on Circuits and Systems. MWSCAS (Cat. No. 01CH37257)*, USA, 2001, vol. 2, pp. 905-908,2001.
- [104] H. Wei, "Analysis of Interference Effect of GPS Satellite Power Enhancement Signal," in *China Satellite Navigation Conference (CSNC) Proceedings: Volume II*, 2022, p. 174, 2022: Springer Nature.
- [105] S. Wang, X. Liu, X. Tang, F. Wang, and Z. Zhuang, "Design of LEO Navigation Signal System Based on Variable Period Spread Spectrum Code," *China Satellite Navigation Conference*, pp. 622-637,2022: Springer.
- [106] M. Li, G. Qin, K. Jiang, Y. Wang, and Q. Zhao, "Performance assessment of real-time orbit determination for the Haiyang-2D using onboard BDS-3/GPS observations," *Advances in Space Research*, 2022.
- [107] M. Fujieda, R. Tabuchi, and T. Gotoh, "A New TWSTFT Modem with Code and Carrier Phases," *The Joint Conference of the IEEE International Frequency Control Symposium and European Frequency and Time Forum (EFTF/IFC)*,USA, , pp. 1-2, 2019.
- [108] V. S. Srinivas and K. Yedukondalu, "Position Domain analysis of modernized GPS Ionosphere-free Code Observations," *URSI Asia-Pacific Radio Science Conference (AP-RASC)*, 2019, pp. 1-4,2019.
- [109] D. Xu, "GPS equatorial ionospheric scintillation signals simulation, characterization, and estimation," *Colorado State University*, 2019.
- [110] P. Steigenberger, S. Thölert, and O. Montenbruck, "Flex power on GPS block IIR-M and IIF," *GPS Solutions*, vol. 23, no. 1, pp. 1-12, 2019.
- [111] T. Y. Mina and G. X. Gao, "Devising high-performing random spreading code sequences using a multi-objective genetic algorithm," *The Proceedings of the 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS)*, USA, pp. 1076-1089,2019.
- [112] P. W. Ward, "A design technique to remove the correlation ambiguity in binary offset carrier (BOC) spread spectrum signals," *The Proceedings*

of the 59th Annual Meeting of The Institute of Navigation and CIGTF 22nd Guidance Test Symposium, USA, pp. 146-155, 2003.

- [113] P. Bolla and K. Borre, "Performance analysis of dual-frequency receiver using combinations of GPS L1, L5, and L2 civil signals," *Journal of Geodesy*, vol. 93, no. 3, pp. 437-447, 2019.
- [114] J. Geng, P. Jiang, and J. Liu, "Integrating GPS with GLONASS for high-rate seismogeodesy," *Geophysical research letters*, vol. 44, no. 7, pp. 3139-3146, 2017.
- [115] L. Wanninger, "Carrier-phase inter-frequency biases of GLONASS receivers," *Journal of Geodesy*, vol. 86, no. 2, pp. 139-148, 2012.
- [116] H. Karimi, "An analysis of satellite visibility and single point positioning with GPS, GLONASS, Galileo, and BeiDou-2/3," *Applied Geomatics*, vol. 13, no. 4, pp. 781-791, 2021.
- [117] S. Revnivvykh, A. Bolkunov, A. Serdyukov, and O. Montenbruck, "Glonass," *Springer Handbook of Global Navigation Satellite Systems: Springer*, pp. 219-245, 2017.
- [118] X. Sun, S. Song, Y. Ji, X. Gan, S. Yan, and X. Jia, "An Unambiguous Synchronization Scheme for GNSS BOC Signals Based on Reconstructed Correlation Function," *Sensors*, vol. 21, no. 6, p. 1982, 2021.
- [119] Y.-F. Tsai, W.-H. Yeh, J.-C. Juang, D.-S. Yang, and C.-T. Lin, "From GPS receiver to GNSS reflectometry payload development for the triton satellite mission," *Remote Sensing*, vol. 13, no. 5, p. 999, 2021.
- [120] E. Rebeyrol, O. Julien, C. Macabiau, L. Ries, A. Delatour, and L. Lestarquit, "Galileo civil signal modulations," *GPS Solutions*, vol. 11, no. 3, pp. 159-171, 2007.
- [121] A. Bumrungrkit, P. Supnithi, S. Saito, and L. M. M. Myint, "A study of equatorial plasma bubble structure using VHF radar and GNSS scintillations over the low-latitude regions," *GPS Solutions*, vol. 26, no. 4, pp. 1-15, 2022.
- [122] O. Julien and C. Macabiau, "New GNSS frequencies, advantages of M-Code, and the benefits of a solitary Galileo satellite: what are the major differences between Galileo and GPS current and forthcoming frequencies?," *Inside GNSS*, vol. 1, no. 4, pp. pp 22-25, 2006.

- [123] M. Foucras, O. Julien, C. Macabiau, and B. Ekambi, "A novel computationally efficient Galileo E1 OS acquisition method for GNSS software receiver," The Proceedings of the 25th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS),USA, 2012, pp. 365-383, 2012.
- [124] C. Fernández-Prades, J. Arribas, L. Esteve, D. Pubill, and P. Closas, "An open source Galileo E1 software receiver," The 6th ESA Workshop on Satellite Navigation Technologies (Navitec) & European Workshop on GNSS Signals and Signal Processing, Noordwijk, pp. 1-8, 2012.
- [125] P. Das, L. Ortega, J. Vilà-Valls, F. Vincent, E. Chaumette, and L. Davain, "Performance limits of GNSS code-based precise positioning: GPS, galileo & meta-signals," *Sensors*, vol. 20, no. 8, p. 2196, 2020.
- [126] A. M. Padokhin, A. A. Mylnikova, Y. V. Yasyukevich, Y. V. Morozov, G. A. Kurbatov, and A. M. Vesnin, "Galileo E5 AltBOC Signals: Application for Single-Frequency Total Electron Content Estimations," *Remote Sensing*, vol. 13, no. 19, p. 3973, 2021.
- [127] M. Powe and J. Owen, "The European GNSS L5/E5 interference environment and the performance of pulsed interference mitigation techniques," The Proceedings of the 17th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2004), USA, pp. 122-131, 2004.
- [128] S. Khan, Y. Zhu, M. Jawad, M. U. Safder, M. H. Jaffery, and S. Javid, "Analysis of the satellite navigational data in the Baseband signal processing of Galileo E5 AltBOC signal," arXiv preprint arXiv:2101.01381, 2021.
- [129] S. Chinnapark, N. Onanong, J. Pattameak, T. Mekpradab, and P. Kenpankho, "Galileo-E6 bandwidth frequency filter design for galileo receiver," *ASEAN Journal of Science and Engineering*, vol. 1, no. 2, pp. 57-62, 2021.
- [130] A. J. Morrison, N. Sokolova, N. Gerrard, A. Rødningsby, C. Rost, and L. Ruotsalainen, "RFI considerations for utility of the Galileo E6 signal," The Proceedings of the 34th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS), pp. 2870-2878, 2021.

- [131] P. Steigenberger, Z. Deng, J. Guo, L. Prange, S. Song, and O. Montenbruck, "BeiDou-3 orbit and clock quality of the IGS Multi-GNSS Pilot Project," *Advances in Space Research*, 2022.
- [132] R. G. Suya, Y.-T. Chen, C. F. Kwong, and P. Zhang, "BeiDou intra-system bias using different precise orbit and clock products," *Measurement*, vol. 191, p. 110804, 2022.
- [133] F. Xia, S. Ye, D. Chen, J. Wu, C. Wang, and W. Sun, "Estimation of antenna phase center offsets for BeiDou IGSO and MEO satellites," *GPS Solutions*, vol. 24, no. 4, pp. 1-15, 2020.
- [134] S. Jin, "Preface: BeiDou navigation satellite system (BDS)/GNSS+: recent progress and new applications," *Advances in Space Research*, vol. 59, no. 3, pp. 751-752, 2017.
- [135] O. Montenbruck, P. Steigenberger, and A. Hauschild, "Broadcast versus precise ephemerides: a multi-GNSS perspective," *GPS solutions*, vol. 19, no. 2, pp. 321-333, 2015.
- [136] O. Montenbruck, P. Steigenberger, and A. Hauschild, "Multi-GNSS signal-in-space range error assessment–Methodology and results," *Advances in Space Research*, vol. 61, no. 12, pp. 3020-3038, 2018.
- [137] J. R. van der Merwe ., "Efficient Multi-Hypothesis Tests for Extended Coherent Acquisition Using Modified Linear Feedback Shift Register Secondary Codes," in *2021 International Conference on Localization and GNSS (ICL-GNSS)*, Finland, pp. 1-8, 2021.
- [138] D. Megnet-Kagi, H. Mathis, P. Flammant, and A. Thiel, "C/A-code synchronization using analog feedback shift registers (AFSR)," *The Proceedings of the 17th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS)*, pp. 32-42, 2004.
- [139] C. F. Prades, "Advanced signal processing techniques for global navigation satellite systems receivers," *Bercelona. Universitat Politecnica de Catalunya*, 2005.
- [140] O. K. Mikhaylova, I. V. Korogodin, and I. V. Lipa, "Universal ranging code generator of GNSS signals," *The European Navigation Conference (ENC)*, pp. 1-10, 2020.
- [141] G. X. Gao, J. Spilker, T. Walter, P. Enge, and T. Pratt, "Code generation scheme and property analysis of broadcast Galileo L1 and E6 signals,"

- The Proceedings of the 19th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS), USA, pp. 1526-1534, 2006.
- [142] S. Wallner, J.-A. Avila-Rodriguez, G. W. Hein, and J. J. Rushanan, "Galileo E1 OS and GPS L1C pseudo random noise codes-requirements, generation, optimization and comparison," The Proceedings of the 20th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2007), USA, pp. 1549-1563, 2007.
 - [143] R. Mu and T. Long, "Design and Implementation of Vector Tracking Loop for High-Dynamic GNSS Receiver," *Sensors*, vol. 21, no. 16, p. 5629, 2021.
 - [144] X. Wang, Y. Yao, C. Xu, Y. Zhao, and H. Zhang, "An improved single-epoch attitude determination method for low-cost single-frequency GNSS receivers," *Remote Sensing*, vol. 13, no. 14, p. 2746, 2021.
 - [145] G. Zhang and L. T. Hsu, "Performance assessment of GNSS diffraction models in urban areas," *Navigation*, vol. 68, no. 2, pp. 369-389, 2021.
 - [146] R. U. R. Lighari, M. Berg, J. Kallankari, A. Parssinen, and E. T. Salonen, "Analysis of the measured RHCP and LHCP GNSS signals in multipath environment," The International Conference on Localization and GNSS (ICL-GNSS), Spain, 2016, pp. 1-6, 2016.
 - [147] Y. Li, K. Yu, X. Chang, T. Jin, and J. Li, "Estimation of Wheat Height With SNR Observations Collected by Low-Cost Navigational GNSS Chip and RHCP Antenna," *Geoscience and Remote Sensing Letters*, vol. 19, pp. 1-5, 2021.
 - [148] M. Socharoentum, H. A. Karimi, and Y. Deng, "A machine learning approach to detect non-line-of-sight GNSS signals in Nav2Nav," The 23rd ITS World Congress, 2016, pp. 10-14, 2016.
 - [149] C. Ruf., "Next generation GNSS-R instrument," The IGARSS 2020-2020 International Geoscience and Remote Sensing Symposium, USA, pp. 3353-3356, 2020.
 - [150] Y. Shin and C. G. Park, "Design of a GNSS Antenna to Prevent LNA Saturation and Intermodulation Caused by S-Band Signals,"

International Journal of Aeronautical and Space Sciences, vol. 21, no. 3, pp. 780-789, 2020.

- [151] Z. Luo, J. Ding, L. Zhao, and M. Wu, "An enhanced non-coherent pre-filter design for tracking error estimation in GNSS receivers," *Sensors*, vol. 17, no. 11, p. 2668, 2017.
- [152] D. Borio, "Robust signal processing for GNSS," in 2017 European Navigation Conference (ENC), USA, pp. 150-158, 2017.
- [153] G. Hein, T. PANY, S. WALLNeR, and J.-H. Won, "Platforms for a future GNSS receiver," *Inside GNSS*, vol. 1, no. 2, pp. 56-62, 2006.
- [154] M. Foucras., "Study on the cross-correlation of GNSS signals and typical approximations," *GPS solutions*, vol. 21, no. 2, pp. 293-306, 2017.
- [155] T. Suzuki and Y. Amano, "NLOS multipath classification of GNSS signal correlation output using machine learning," *Sensors*, vol. 21, no. 7, p. 2503, 2021.
- [156] F. Manta, G. Occhipinti, E. M. Hill, A. Perttu, J. Assink, and B. Taisne, "Correlation between GNSS-TEC and eruption magnitude supports the use of ionospheric sensing to complement volcanic hazard assessment," *Journal of Geophysical Research: Solid Earth*, vol. 126, no. 2, p. e2020JB020726, 2021.
- [157] F. Zhou ., "GNSS Signal Acquisition Algorithm Based on Two-Stage Compression of Code-Frequency Domain," *Applied Sciences*, vol. 12, no. 12, p. 6255, 2022.
- [158] K. Chae and S. Yoon, "Design of a novel PN code based on genetic algorithm for rapid GNSS signal acquisition," *European Navigation Conference (ENC), USA*, pp. 1-4, 2019.
- [159] J. T. Curran, G. Lachapelle, and C. C. Murphy, "Digital GNSS PLL design conditioned on thermal and oscillator phase noise," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 48, no. 1, pp. 180-196, 2012.
- [160] W. Qiu, Q. Zeng, R. Xu, J. Liu, J. Shi, and Q. Meng, "A multipath mitigation algorithm for GNSS signals based on the steepest descent approach," *Satellite Navigation*, vol. 3, no. 1, pp. 1-11, 2022.'

- [161] J. S. Malik and U. I. Bhatti, "Remote sensing of ocean, ice and land surfaces using bistatically reflected GNSS signals from low Earth orbit," 4th International Conference on Aerospace Science and Engineering (ICASE), Pakistan, 2015, pp. 1-6, 2015.
- [162] P. Pagani, F. T. Talom, P. Pajusco, and B. Uguen, Ultra-wideband radio propagation channels: a practical approach. John Wiley & Sons, 2013.
- [163] A. Chen, A. Chabory, A.-C. Escher, and C. Macabiau, "Development of a GPS deterministic multipath simulator for an efficient computation of the positioning errors," 2009.
- [164] I. P. Portella, A. de O Moraes, M. da Silva Pinho, J. Sousasantos, and F. Rodrigues, "Examining the tolerance of GNSS receiver phase tracking loop under the effects of severe ionospheric scintillation conditions based on its bandwidth," *Radio Science*, vol. 56, no. 6, pp. 1-11, 2021.
- [165] L.-T. Hsu, "GNSS multipath detection using a machine learning approach," 20th International Conference on Intelligent Transportation Systems (ITSC), Japan, 2017, pp. 1-6, 2017.
- [166] F. Bastide, "Analysis of the feasibility and interests of Galileo E5a/E5b and GPS L5 signals for use with civil aviation," Ecole Nationale de l'Aviation Civile (ENAC), 2004.
- [167] A. Blais, N. Couellan, and E. Munin, "A novel image representation of GNSS correlation for deep learning multipath detection," *Array*, vol. 14, p. 100167, 2022.
- [168] M. Li, G. Huang, L. Wang, W. Xie, and F. Yue, "Performance of Multi-GNSS in the Asia-Pacific Region: Signal Quality, Broadcast Ephemeris and Precise Point Positioning (PPP)," *Remote Sensing*, vol. 14, no. 13, p. 3028, 2022.
- [169] Y. Qi, Z. Yao, Y. Gao, and M. Lu, "Robust unambiguous ranging technique for BDS-3 B1 wideband composite signals," *GPS Solutions*, vol. 26, no. 4, pp. 1-15, 2022.
- [170] H. Li, P. Borhani-Darian, P. Wu, and P. Closas, "Deep Neural Network Correlators for GNSS Multipath Mitigation," *IEEE Transactions on Aerospace and Electronic Systems*, 2022.

- [171] R. Yang, K.-V. Ling, E.-K. Poh, and Y. Morton, "Generalized GNSS signal carrier tracking: part I—modeling and analysis," *Transactions on aerospace and electronic systems*, vol. 53, no. 4, pp. 1781-1797, 2017.
- [172] G. Brodin and P. Daly, "GNSS code and carrier tracking in the presence of multipath," *International journal of satellite communications*, vol. 15, no. 1, pp. 25-34, 1997.
- [173] A. Hauschild and O. Montenbruck, "A study on the dependency of GNSS pseudorange biases on correlator spacing," *GPS solutions*, vol. 20, no. 2, pp. 159-171, 2016.
- [174] P. Benevides, G. Nico, J. Catalão, and P. M. Miranda, "Analysis of Galileo and GPS integration for GNSS tomography," *Transactions on geoscience and remote sensing*, vol. 55, no. 4, pp. 1936-1943, 2016.
- [175] P. Steigenberger and O. Montenbruck, "Galileo status: orbits, clocks, and positioning," *GPS solutions*, vol. 21, no. 2, pp. 319-331, 2017.
- [176] F. Sousa, F. Nunes, A. Negrinho, P. Fernandes, and P. Boto, "Signal Quality Monitoring Aspects in GNSS Signals Affected by Evil Waveforms," in *2022 10th Workshop on Satellite Navigation Technology (NAVITEC)*, Netherlands, pp. 1-14, 2022.
- [177] J. Ma, Y. Yang, L. Ye, L. Deng, and H. Li, "Dual-Sideband Constant-Envelope Frequency-Hopping Binary Offset Carrier Multiplexing Modulation for Satellite Navigation," *Remote Sensing*, vol. 14, no. 16, p. 3871, 2022.
- [178] T.-L. Kao and J.-C. Juang, "Weighted discriminators for GNSS BOC signal tracking," *GPS solutions*, vol. 16, no. 3, pp. 339-351, 2012.
- [179] A. Pirsiavash, A. Broumandan, G. Lachapelle, and K. O'Keefe, "GNSS measurement weighting to improve navigation integrity in multipath environments," *The 6th ESA International Colloquium on Scientific and Fundamental Aspects of the Galileo*, p. 8, 2017.
- [180] N. I. Ziedan, "Enhancing GNSS mobile positioning in urban environments through utilization of multipath prediction and consistency analysis," *The 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS)*, pp. 3469-3483, 2019.

- [181] S. Cancela ., "Field testing of GNSS user protection techniques," The Proceedings of the 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2019), pp. 1824-1840,2019.
- [182] A. Kakkar, A. Agrawal, M. Kumar, and S. Kibe, "Analysis of advanced FEC versus traditional FEC in GNSS data structures," The Integrated Communications, Navigation, and Surveillance Conference Proceedings,USA, pp. P6-1-P6-10,2011.
- [183] X. Qian and S. Jin, "Estimation of snow depth from GLONASS SNR and phase-based multipath reflectometry," Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 9, no. 10, pp. 4817-4823, 2016.
- [184] L.-T. Hsu, S.-S. Jan, P. D. Groves, and N. Kubo, "Multipath mitigation and NLOS detection using vector tracking in urban environments," *Gps Solutions*, vol. 19, no. 2, pp. 249-262, 2015.
- [185] M. Irsigler, "Multipath propagation, mitigation and monitoring in the light of Galileo and the modernized GPS," Diss. Universität der Bundeswehr Munchen, 2008.
- [186] A. Pirsiavash, A. Broumandan, G. Lachapelle, and K. O'Keefe, "GNSS code multipath mitigation by cascading measurement monitoring techniques," *Sensors*, vol. 18, no. 6, p. 1967, 2018.
- [187] M. Caamano, O. G. Crespillo, D. Gerbeth, and A. Grosch, "Detection of GNSS Multipath with Time-Differenced Code-Minus-Carrier for Land-Based Applications," The European Navigation Conference (ENC),Germany, pp. 1-12,2020.
- [188] A. Pirsiavash, A. Broumandan, and G. Lachapelle, "Characterization of signal quality monitoring techniques for multipath detection in GNSS applications," *Sensors*, vol. 17, no. 7, p. 1579, 2017.
- [189] Y. Wang and Z. Huang, "MEDLL on-strobe correlator: a combined anti-multipath technique for GNSS signal tracking," The Journal of Navigation, vol. 73, no. 3, pp. 658-677, 2020.

- [190] T. Marathe, S. Daneshmand, and G. Lachapelle, "Assessment of measurement distortions in GNSS antenna array space-time processing," *International Journal of Antennas and Propagation*, vol. 2016, 2016.
- [191] Y. Sun, Z. Yao, and M. Lu, "Extended Double-delta Correlator Technique for GNSS Multipath Mitigation," *Transactions on Aerospace and Electronic Systems*, 2022.
- [192] G. Chang, T. Xu, C. Chen, B. Ji, and S. Li, "Switching position and range-domain carrier-smoothing-code filtering for GNSS positioning in harsh environments with intermittent satellite deficiencies," *Journal of The Franklin Institute*, vol. 356, no. 9, pp. 4928-4947, 2019.
- [193] P. A. Hwang, G. A. McGraw, and J. R. Bader, "Enhanced differential GNSS carrier-smoothed code processing using dual frequency measurements," ed: Google Patents, 2001.
- [194] P. Closas Gómez, *Bayesian signal processing techniques for GNSS receivers: from multipath mitigation to positioning*. Universitat Politècnica de Catalunya, 2009.
- [195] P. Stoica and M. Viberg, "Maximum likelihood parameter and rank estimation in reduced-rank multivariate linear regressions," *Transactions on signal processing*, vol. 44, no. 12, pp. 3069-3078, 1996.
- [196] A. Calabia ., "Low-Latitude Ionospheric Responses and Coupling to the February 2014 Multiphase Geomagnetic Storm from GNSS, Magnetometers, and Space Weather Data," *Atmosphere*, vol. 13, no. 4, p. 518, 2022.
- [197] R. B. Langley, P. J. Teunissen, and O. Montenbruck, "Introduction to GNSS," *The Springer handbook of global navigation satellite systems*: Springer, 2017, pp. 3-23.
- [198] Y. Zhu I., "Sensing sea ice based on Doppler spread analysis of spaceborne GNSS-R data," *Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 13, pp. 217-226, 2019.
- [199] G. X. Gao, M. Sgammini, M. Lu, and N. Kubo, "Protecting GNSS receivers from jamming and interference," *Proceedings of the IEEE*, vol. 104, no. 6, pp. 1327-1338, 2016.

- [200] W. Zhou, Y. Liu, L. Huang, B. Ji, L. Liu, and S. Bian, "Multi-constellation GNSS interferometric reflectometry for the correction of long-term snow height retrieval on sloping topography," *GPS Solutions*, vol. 26, no. 4, pp. 1-16, 2022.
- [201] J. Paziewski, "Multi-constellation single-frequency ionospheric-free precise point positioning with low-cost receivers," *GPS Solutions*, vol. 26, no. 1, pp. 1-11, 2022.